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GEOLOGICAL INVESTIGATIONS IN NEW BRUNSWICK FOR 2003

Gwen L. Martin, editor

2004

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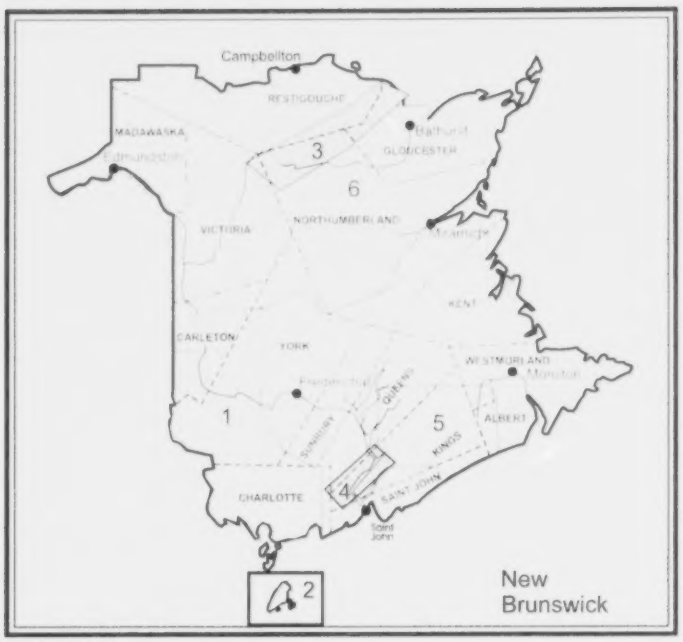

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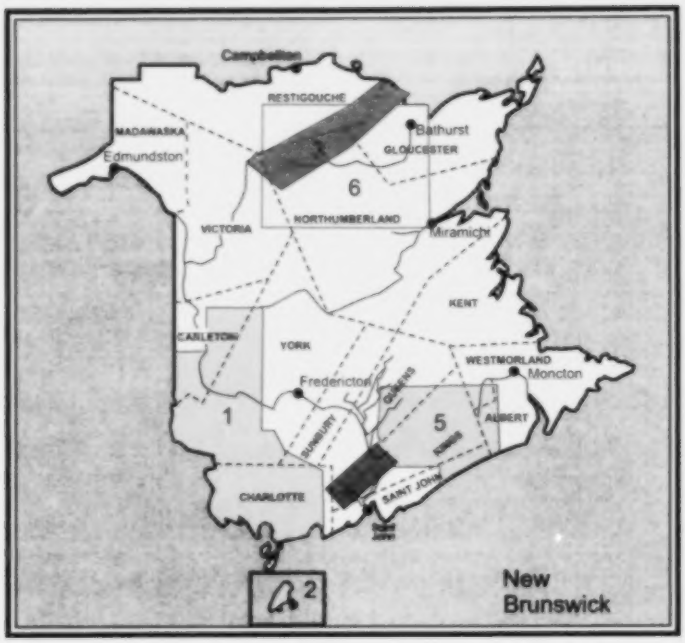

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LEVELLING METHODS FOR REGIONAL TILL GEOCHEMISTRY DATA FROM SOUTHWESTERN NEW BRUNSWICK

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ALLARD, S. 2004. Levelling methods for regional till geochemistry data from southwestern New Brunswick. *In* Geological Investigations in New Brunswick for 2003. *Edited by* Gwen L. Martin. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division, Mineral Resource Report 2004-4, pp. 1–20.

The current geochemical database for southwestern New Brunswick comprises information gathered over numerous years from several laboratories using a variety of analytical techniques. As a result, element values obtained from one survey can differ from element values of another survey, despite their similar parametric characteristics. To mitigate these inconsistencies and produce a more accurate regional database, levelling corrections can be made. Levelling is the practice of applying a correction factor to the values of one survey to make them comparable to the values of another. It is particularly crucial when comparing results from multiple surveys or when compiling databases and contour maps into a regional-scale publication. The recent, successful levelling of till geochemistry data from southwestern New Brunswick relied on the techniques of parametric normalization and quantile regression normalization to level 24 elements. The work represents a pilot project for the levelling of till geochemistry data in New Brunswick and is the first levelling project of this type ever conducted by the provincial Department of Natural Resources. To optimize reliability of the levelling process and to minimize levelling requirements in the future, it would be advisable to reduce the diversity of analytical methods and laboratories used.

La base de données géochimique existante du Sud-Ouest du Nouveau-Brunswick comprend des données recueillies au fil des ans auprès de plusieurs laboratoires utilisant diverses techniques d'analyse. Ainsi, les concentrations d'éléments obtenues au moyen d'une étude donnée diffèrent généralement des concentrations d'éléments d'une autre étude, en dépit de leurs caractéristiques paramétriques semblables. Il est possible d'effectuer des corrections de nivellement pour atténuer ces divergences et produire une base de données régionale utile. Le nivellement est la pratique qui consiste à appliquer un facteur de correction aux valeurs d'une étude pour les rendre comparables aux valeurs d'une autre étude. Il s'avère particulièrement crucial lorsqu'on compare les résultats de plusieurs analyses ou lors de la compilation de bases de données et de cartes en courbes de niveau dans une publication régionale. L'auteur du récent nivellement fructueux de données géochimiques des tills du Sud-Ouest du Nouveau-Brunswick s'est appuyé sur les techniques de la normalisation

paramétrique et de la normalisation de la régression par quantile pour niveler 24 éléments différents. Ces travaux représentent un projet pilote en ce qui concerne le nivellement des données géochimiques des tills au Nouveau-Brunswick — premier projet du genre jamais réalisé par le ministère provincial des Ressources naturelles. Pour minimiser les besoins de nivellement dans l'avenir, il faudrait réduire la diversité des méthodes d'analyse et des laboratoires de manière à optimiser la fiabilité du processus de nivellement.

INTRODUCTION

The current, ongoing program of till sampling in southwestern New Brunswick began in 1990. Since its inception, 2568 till samples have been collected from sections of the NTS 21 G and 21 J map areas (Fig. 1). Of these, 2122 samples are basal tills, those being lodgment till, basal-meltout till, and deformation till (Brodzikowski and Van Loon 1987). Seaman (2001) and Allard (2003) describe sampling methodologies used during collection.

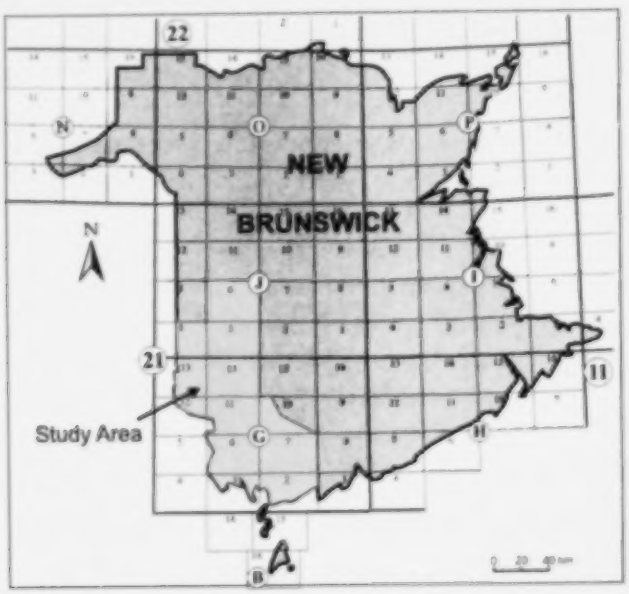

Figure 1. Location of study area for levelling of till geochemistry data.

Geochemical data obtained from these samples were plotted on twelve NTS map sheets at the scale of 1: 50 000: nine maps in the 21 G series and three maps in the 21 J series (Fig. 1). The data were derived from several laboratories that employed a range of analytical methods and digestion techniques (Table 1). Some map authors used ACME® Analytical Laboratories Ltd. in Vancouver, British Columbia, for Inductively Coupled Plasma-Mass Spectrometry analysis (ICP-MS); and Becquerel Laboratories Inc. in Mississauga, Ontario, for Instrumental Neutron Activation Analysis (INAA). Other authors used Activation Laboratories Ltd. (Actlabs®) in Ancaster, Ontario, for both

Table 1. Till geochemistry coverage in southwestern New Brunswick, 1990–2004.

Map Sheet (1:50 000)	NTS Number	Sampling Year	Reference Source	Analytical Method	Laboratory	Digestion Method (for ICP only)
St. George	21 G/2	2003	Pronk et al. (in prep.)	ICP-MS	ACME	Aqua Regia
				INAA	Becquerel	
St. Stephen	21 G/3	2002	Pronk et al. (2003a)	ICP-MS	ACME	Aqua Regia
				INAA	Becquerel	
Rollingdam	21 G/6	2001	Allard (2003) Pronk et al. (2002)	ICP-MS	ACME	Aqua Regia
				INAA	Becquerel	
McDougall Lake	21 G/7	2000 2001	Pronk et al. (2002)	ICP-MS	ACME	Aqua Regia
				INAA	Becquerel	
Fredericton Junction	21 G/10	2002	Pronk et al. (2003b)	ICP-MS	ACME	Aqua Regia
				INAA	Becquerel	
McAdam	21 G/11	1991 1992 1993 1994	Stumpf (1995) Seaman (2003a)	INAA	Actlabs	
				ICP-OES	Actlabs	Aqua Regia
Forest City	21 G/12	1990	Seaman (1992, 1993b, 1999a)	INAA	Actlabs	
				AAS *	DNR	
Fosterville	21 G/13	1990 1992 1993	Seaman (1993a, 1994, 1999a)	INAA	Actlabs	
				ICP-OES *	Actlabs	Aqua Regia
				AAS *	DNR	
Canterbury	21 G/14	1990 1991 1995	Balzer (1992) Seaman (in press)	INAA	Actlabs	
				ICP-OES *	Actlabs	4-acid
				AAS *	DNR	
Millville	21 J/3	1995 1996 1997 1998	Seaman (1999b)	INAA	Actlabs	
				ICP-OES	Actlabs	4-acid
Woodstock	21 J/4	1999	Seaman (2000)	INAA	Actlabs	
				ICP-OES	Actlabs	4-acid
Coldstream	21 J/6	1998 2000 2001 2002	Seaman (2001, 2002, 2003b)	INAA	Actlabs	
				ICP-OES	Actlabs	4-acid

Notes: 1. * = Partial dataset. 2. Aqua Regia digestion uses HNO_3 and HCl dissolution. 4-acid digestion uses HF, HNO_3, $HClO_4$, and HCl dissolution.

INAA and Inductively Coupled Plasma-Optical Emission Spectrometry analysis (ICP-OES). Base-metal analyses for the Fosterville, Forest City, and Canterbury map sheets were conducted at the Atomic Absorption Spectroscopy (AAS) analytical laboratory of the New Brunswick Department of Natural Resources (DNR) in Fredericton. Departmental staff performed the AAS analyses prior to closure of the laboratory in 1993.

This diversity of analytical techniques and laboratories has produced a database in which element values of one survey tend to differ from the same element values of another survey, despite their similar parametric characteristics (Grunsky, in press). To offset the inconsistencies and produce a more accurate regional database, levelling corrections should be used where required. Levelling is the practice of applying a correction factor to the values of one survey to make them comparable to the values of another.

Until recently, the New Brunswick Department of Natural Resources performed no levelling of geochemical data. Information simply was collected, analyzed, and published as tabulated data or as maps at the 1:50 000 scale, obviating the need for levelling. These publications have successfully contributed to the identification of new exploration targets for prospectors and junior mining companies operating in southwestern New Brunswick.

When comparing results from multiple surveys, however, or when compiling data from the 1:50 000 maps into regional-scale maps covering a larger area, levelling becomes important. Regional maps are invaluable for assessing broader geochemical trends or highlighting prospective exploration targets. Yet the information on maps produced from a non-levelled database can be misleading. Given the rising demand for promotional maps and for website delivery of the geochemical database, the establishment and maintenance of a levelled database assumes greater significance.

LEVELLING SCENARIOS

The current project to level the disparate geochemical data began in 2003. A total of 24 elements were levelled in order to produce regional-scale, coloured contour maps of southwestern New Brunswick showing the till geochemistry and element association plots. The elements consisted of As, Au, Ba, Ce, Co, Cr, Cs, Cu, Eu, Fe, Hg, La, Lu, Mn, Ni, Pb, Rb, Sb, Sm, Tb, Th, U, Yb, and Zn.

Data for Cu, Mn, Ni, Pb, and Zn were levelled to Actlabs® ICP-OES. Data for all other elements were levelled to Actlabs® INAA. Levelling corrections were applied where significant discrepancies in elemental data existed. The discrepancies resulted from one or more of the following three circumstances.

1. Varying Analytical Techniques

Where a complete data set did not exist for a given analytical technique, levelling was conducted to create a new, comprehensive data set. Combining data obtained from different analytical methods without going through the levelling process usually produces unreliable results. In this case, data from AAS (Aqua Regia (AR)), conducted by DNR staff, was levelled to fit data from ICP-OES (AR), conducted by Actlabs®. The AAS values generally were comparable to ICP-OES values. Both possessed similar parametric characteristics, as determined by quantile analysis of standard reference data included in the surveys. No levelling of AAS with ICP-OES was required for Cu. The ICP plots for Mn, Ni, Pb, and Zn, however, all required some degree of levelling AAS (AR) with ICP-OES (AR).

In addition, the ACME ICP-MS results (which relied on AR digestion) had to be levelled with the Actlabs® ICP-OES results (which relied on 4-acid digestion) to produce regional data for Cu, Mn, Ni, Pb, and Zn. The practice of levelling ICP-MS (AR) with ICP-OES (4-acid) generally is not recommended. The 4-acid, near-total extraction method relies on hydrochloric, nitric, perchloric, and hydrofluoric acids, and provides much a stronger dissolution than does the AR, partial-extraction method.

These inherent differences in digestion can produce differential breakdown of specific minerals, which potentially could result in over-concentration of some elements and under-concentration of others, depending on the parent mineralogy. Nonetheless, as mentioned earlier, quantile analysis of standard data shows that values obtained from the two methods exhibit similar parametric characteristics and therefore can be levelled.

2. Consistent Analytical Technique and Varying Laboratories

Both Becquerel and Actlabs® laboratories were used to conduct INAA. Standard data indicate that values obtained from INAA methods employed at each laboratory are comparable for most elements. The data required only minimal levelling, and that for only a few elements: Cr, La, Lu, Rb, Sm, Ta, and Yb.

3. Consistent Analytical Technique and Laboratory; Changes in Detection Parameters and/or Digestion Methods

Many laboratory techniques are continually being upgraded. Since commencement of the till-sampling project, variables such as the detection limits, accuracy, precision, and control over digestion conditions all have been improved. Corrections were applied as required to take these factors into account.

In some cases, a laboratory used the same analytical technique for their runs but relied on two different ICP digestion methods. The Actlabs® laboratory, for example, processed two of its six ICP-

OES runs (those for the Fosterville and McAdam map sheets) using the AR digestion method instead of the 4-acid digestion method. Despite this difference, almost all preliminary plots for the current project showed no substantial contour disruptions at boundaries of the 1:50 000 maps where the digestion method varied from one sheet to the next. Although only Cu, Mn, Ni, Pb, and Zn were reported as ICP contour plots, they displayed no notable discrepancy in the magnitude of values obtained from each digestion technique. These observations support Hoffman (1999), who found that analytical results for some elements, including base metals, were comparable when using different ICP digestion methods.

One exception — the McAdam map sheet — displayed noticeable edge effects on the preliminary contour plot. This was manifested as Pb and Zn concentrations that were considerably lower than those plotted on surrounding map sheets. The anomalies cannot be attributed to variable digestion techniques, because the Fosterville map was compiled from data using the same digestion method and displayed no such discontinuities with adjoining sheets.

The relatively low Zn and Pb values of the McAdam data therefore must be the consequence of analytical drift and/or procedural error associated with the AR digestion procedure prior to automation of the dissolution process by Actlabs®. These discrepancies have been accommodated in the levelling process.

LEVELLING TECHNIQUES

Correction factors for variable data were computed using two levelling techniques: parametric normalization and quantile regression normalization (Darnley et al. 1995). For some situations, a combination of both techniques was required. When applied to levelling, the term 'normalization' is used in its mathematical sense — that is, referring to the process of adjusting the representation of a quantity to remain within a prescribed range (Parker 1974) — rather than in its statistical sense (Darnley et al. 1995).

Parametric Normalization

Parametric normalization can be applied where several samples from the survey needing to be levelled have been re-analyzed using the technique applied in the reference survey, or when standard reference material (SRM) data exist for both surveys. These control data from a same-site sample, or standards, are displayed as x-y plots with similar x- and y-axis scaling.

The reference survey(s) data are plotted against the x axis, and data from the survey to be levelled are plotted against the y axis. If the resulting data plot as a 45° diagonal, levelling is not required (Fig. 2a). If the data plot away from the diagonal but show a linear relationship to it, a correction factor can be applied and the data levelled (Fig. 2b). For example, if the data show a

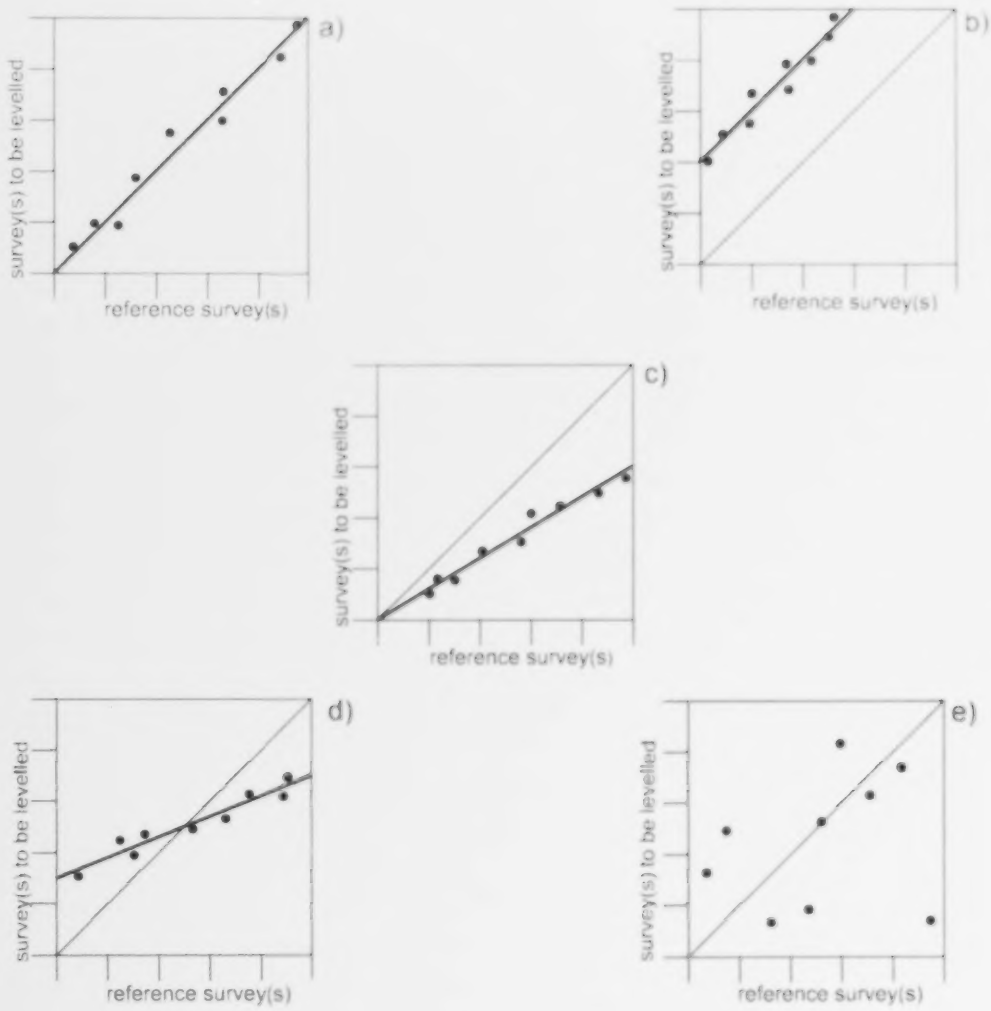

Figure 2. Potential scenarios that require parametric levelling, from Darnley et al. (1995)
a) Slope is at 45°, and no levelling is needed.
b) Slope is parallel to the diagonal, but above or below it. Data need a shift correction.
c) Slope varies from the diagonal. Data need a multiplier correction.
d) Contrast exists between y-axis intersect and data slope. Data need a shift correction and a multiplier correction.
e) Levelling is not possible.

variation in the y-axis intercept, but still plot parallel to the diagonal, either above or below it, a shift correction can be made through simple addition or subtraction. If the slope of the data varies from the diagonal, a multiplier correction equal to the variation in slope will adequately level the data (Fig. 2c). If a contrast exists between the y-axis intercept and the data slope, then both a shift and a multiplier correction are required (Fig. 2d). Levelling is not possible when the data plot randomly about the diagonal with no discernable slope.

Drawing a linear regression line through the data helps to better assess the spatial relationship between the intercept and data slope, relative to 45°. Where a large quantity of control data exists (as in the Fosterville survey, which required 28 re-analyses to level AAS with ICP-OES), then ten quantiles are calculated and plotted instead of the entire data.

Quantile Regression Normalization

Quantile regression normalization (QRN) is used when control data are unavailable to facilitate parametric levelling (Conradsen et al. 1991). Unlike crude levelling procedures of the past, in which one data set was levelled to another simply by compensating for their discrepancy in mean value, QRN requires multiple 'control points' or ten quantile values. To use this levelling technique, survey areas must have similar environmental characteristics. Darnley et al. (1995) state: "For this procedure to be valid, data must be available from a common geochemical landscape in two or more surveys…with similar bedrock that have undergone similar erosional and secondary environmental histories." This technique should be used with caution and applied only to surveys showing similar bedrock characteristics and geochemical relief. Adjacent surveys tend to be the best candidates for QRN.

The QRN process selects multiple surveys as the so-called reference to which other surveys are levelled. Ten quantile values, corresponding to the 10^{th}, 20^{th}…, 80^{th}, 90^{th}, and 95^{th} percentiles, are calculated from the survey data to be levelled and the combined data of the 'reference' survey. These values are displayed on an x-y plot with similar x- and y-axis scaling, and the data sets are levelled using the same procedure described for parametric normalization.

One must be careful not to overlevel the data or to apply levelling in circumstances where it is not warranted. The goal of geochemical compilation maps and databases is to identify anomalies at the regional scale, not to mask them by minimizing their surface expression. Levelling is partly a subjective process, and to successfully apply a correction factor, one must be comfortable with a degree of ambiguity. There is no exact solution to a levelling problem, and two workers may reach slightly different conclusions using the same data.

The Levelling Process in Action, Using Zinc Data

Most elements in the till geochemistry database for southwestern New Brunswick required only minimal normalization. The Zn data set, however, underwent three degrees of levelling and involved most of the levelling situations just described. It also necessitated the amalgamation of three data sources: 1) ICP-OES data from 21 G/11, 13, 14, 21 and 21 J/3, 4, and 6, 2) a lesser quantity of AAS data from 21 G/12 to 14, and 3) ICP-MS data from 21 G/2, 3, 6, 7, and 10 (Table 1). The Zn data set thus provides a good demonstration of how to conduct a step-by-step levelling procedure.

Table 2. Levelling Step 1: Levelling AAS Zn data with ICP-OES Zn data.

	Zn values (ppm) of Fosterville samples		
	ICP-OES (Aqua Regia) data from Actlabs	AAS (Aqua Regia) data from DNR	Correction Factor: ICP-OES = AAS x 1.1
no. of samples	28	28	
minimum	43	40	
maximum	108	138.9	
mean	67	62.60	
10th percentile	51.70	45.93	50.52
20th	53.80	51.82	57.00
30th	59.00	52.50	57.75
40th	60.60	55.30	60.83
50th	63.00	57.20	62.92
60th	67.60	62.44	68.68
70th	74.70	64.90	71.39
80th	75.60	70.86	77.95
90th	87.95	80.41	88.45
95th	96.65	87.59	96.35

Levelling Step 1

The first step in the levelling process required normalizing the AAS data with the ICP-OES data. The presence of sufficient control data in the form of multiple re-analyses permitted the parametric normalization technique to be applied. Data from each duplicate sample were not used directly in the levelling process. Instead, the process relied on quantiles corresponding to the 10^{th}, 20^{th}, 30^{th} ..., 80^{th}, 90^{th}, and 95^{th} percentiles (Table 2). A minor discrepancy existed between the corresponding ICP-OES and AAS percentile values (Fig. 3), but was adequately levelled by a simple multiplier correction factor of 1.1, as shown below.

ICP-OES values for Zn ppm = AAS values for Zn ppm x 1.1

Levelling Step 2

The second step required using parametric normalization to level ICP-MS data from map sheets 21 G/2, 3, 6, 7, and 10 with ICP-OES data from sheets 21 G/11, 13, 14, and 21 J/3, 4, and 6. The control data comprised two sets of standard reference materials: Set 1 consisted of Geological Survey of Canada standards TILL-1, -2, -3, -4, and STSD-4 (Lynch 1990, 1996); Set 2 consisted

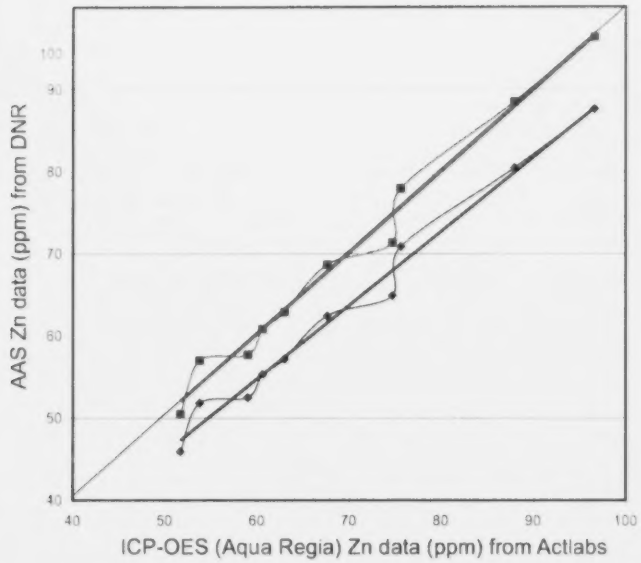

Figure 3. ICP-OES Zn values from Actlabs vs AAS Zn values from DNR. The Zn x-y plot is used to level AAS data with ICP-OES data from the Forest City and Fosterville surveys.
1. Straight blue and red lines represent linear regression trend lines.
2. Blue data line represents contrast between ICP-OES data and unlevelled AAS data.
3. Red data line represents contrast between ICP-OES data and levelled AAS data.
4. Red and blue squares correspond to the percentile values. From left to right: 10th, 20th, 30th, ... 90th, 95th percentiles.

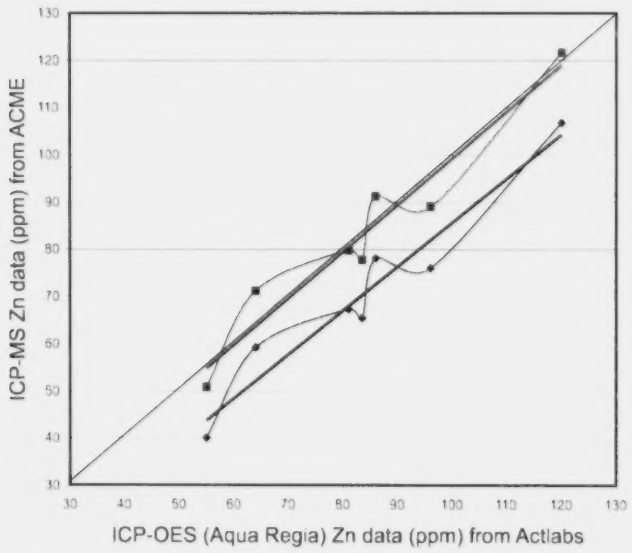

Figure 4. ICP-OES Zn values from Actlabs vs ICP-MS Zn values from ACME. The Zn x-y plot is used to level ICP-MS data with ICP-OES data.
1. Straight blue and red lines represent linear regression trend lines.
2. Blue data line represents contrast between ICP-OES data and unlevelled ICP-MS data.
3. Red data line represents contrast between ICP-OES data and levelled ICP-MS data.
4. Red and blue squares correspond to the percentile values, as listed above.

Table 3. Levelling Step 2: Levelling ICP-MS Zn data with ICP-OES Zn data

	Zn values (ppm) of Fosterville samples		Correction Factor: ICP-OES = (ICP-MS + 8) x 1.06
	ICP-OES (4-acid) data from Actlabs	ICP-MS (Aqua Regia) data from ACME	
no. of samples	8 standards	8 standards	
minimum	55	40	
maximum	3275	3358.5	
mean	482.6	481.4	
TILL-3	55	40	50.88
TILL-4	64	59.2	71.232
NB-CS1	81	67.3	79.818
TILL-1	83.5	65.43	77.8358
STSD-4	86	78.1	91.266
NB-02	96	76	89.04
TILL-2	120	106.8	121.688
NB-01	3275	3358.5	3568.49

of New Brunswick Department of Natural Resources standards NB-01, NB-02, and NB-CS1 (Table 3). Because these standards have undergone multiple runs of analyses using both the ICP-MS and ICP-OES techniques, their average values can safely be used in the levelling process (Table 3).

ICP-MS values generally were lower than ICP-OES values, except in the upper register of analysis (*see* NB-01 on Table 3). Even so, the two data sets demonstrated a linear relationship and thus could be levelled (Fig. 4). A shift correction and a slight multiplier correction were required to normalize the data, as shown below.

ICP-OES values for Zn ppm = (ICP-MS values for Zn ppm + 8) x 1.06

This formula shows that 4-acid digestion extracted an average of 8 ppm more Zn than did AR digestion. The discrepancy does not necessarily reflect parent mineralogy of the collected samples but instead reflects the mineralogy of standard reference materials (SRMs) listed on Table 3. For the purpose of this levelling exercise, it is assumed that mineral compositions of both the samples and the SRMs are comparable. Some SRMs in fact were collected from southwest New Brunswick; however, the discrepancy raises questions about reliability of the levelled ICP-OES data.

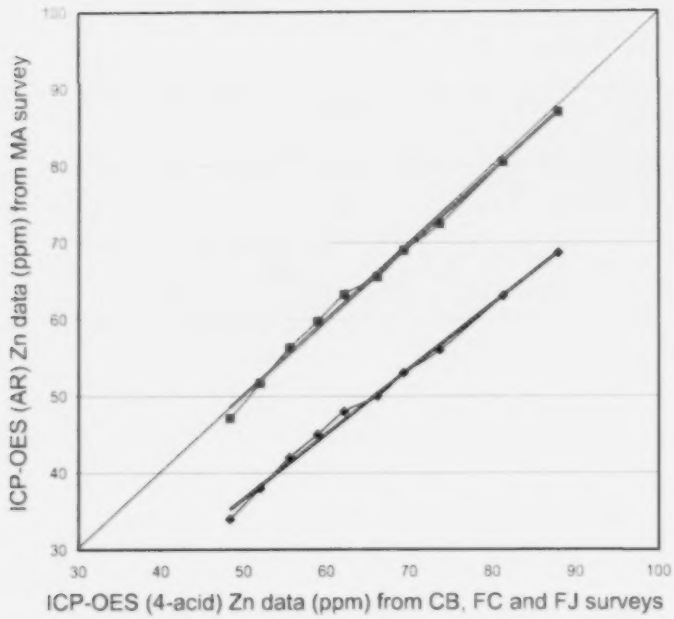

Figure 5. Zn x-y plot used to level ICP-OES data from McAdam (MA) survey with combined ICP-OES data from Canterbury (CA), Forest City (FC), and Fredericton Junction (FJ) surveys.
1. Straight blue and red lines represent linear regression trend lines.
2. Blue data line represents contrast between the (CB, FC, FJ) ICP-OES data and unlevelled (MA) ICP-MS data.
3. Red data line represents contrast between the (CB, FC, FJ) ICP-OES data and levelled (MA) ICP-MS data.
4. Red and blue squares correspond to the percentile values. From left to right: 10^{th}, 20^{th}, 30^{th}, ... 90^{th}, 95^{th} percentiles.

Levelling Step 3

The third and final step was to normalize the McAdam survey values with those on adjoining map sheets. The preliminary regional contour plots for Zn (that is, the values obtained from the levelling of ICP-OES with ICP-MS performed in Step 2) showed considerable edge effects for the McAdam survey. As noted earlier, the anomalously low base-metal values of the McAdam survey evidently resulted from analytical drift and/or variations in the Aqua Regia digestion peculiar to that survey. Zn values on the McAdam map sheet do not appear to accurately reflect the geochemical relief when compared with Zn values on adjacent maps. For this reason, quantile regression was performed.

Combined data from the Canterbury (4-acid digestion), Forest City (AR digestion), and Fredericton Junction (AR digestion) surveys were selected as the 'reference' to which the McAdam (AR digestion) survey was levelled (Table 4). Their suitability as a reference data set was based on three factors: 1) the reference survey areas are geographically adjacent to the McAdam survey area, 2) the reference areas have bedrock similar to that in the McAdam map area, and 3) the reference data had geochemical values in the range of background to threshold-anomalous. Table 4 lists the

Table 4. Levelling Step 3: Levelling Zn values from McAdam survey with Zn values from Canterbury, Fredericton Junction, and Rollingdam surveys.

	Zn (ppm) of (ICP-OES + AAS) and ICP-MS for CB, FC, FJ	Zn (ppm) of (ICP-OES + AAS) and ICP-MS for MA	Correction Factor: MA = [(CB, FC, FJ) + 7] x 1.15
no. of samples	443	229	
minimum	33.88	16.00	
maximum	152.79	80.00	
mean	64.13	47.77	
10th percentile	48.30	34.00	47.15
20th	51.93	38.00	51.75
30th	55.50	42.00	56.35
40th	58.90	45.00	59.80
50th	62.12	48.00	63.25
60th	66.12	50.00	65.55
70th	69.30	53.00	69.00
80th	73.65	56.00	72.45
90th	81.29	63.00	80.50
95th	87.93	68.60	86.94

Notes: 1. CB = Canterbury survey, FC = Forest City, FJ = Fredericton Junction, MA = McAdam.
2. CB used 4-acid digestion; FC, FJ, and MA used Aqua Regia digestion.

discrepancy in values between the data sets, and Figure 5 shows their linear relationship. A shift correction and slight multiplier correction were sufficient to level the sets, as given below.

MA ICP-OES values for Zn ppm = [(CB, FC, and FJ ICP-OES values for Zn ppm) + 7] x 1.15

where MA = McAdam survey, CB = Canterbury survey,
FC = Forest City survey, and FJ = Fredericton Junction survey

Figures 6 and 7 respectively show how the Zn contour plots appeared before and after being levelled to ICP-OES. The data have been contoured on the basis of their percentiles. The base map for the plots is an excerpt of Map NR-1 (New Brunswick Department of Natural Resources and Energy 2000) at the scale of 1:500 000.

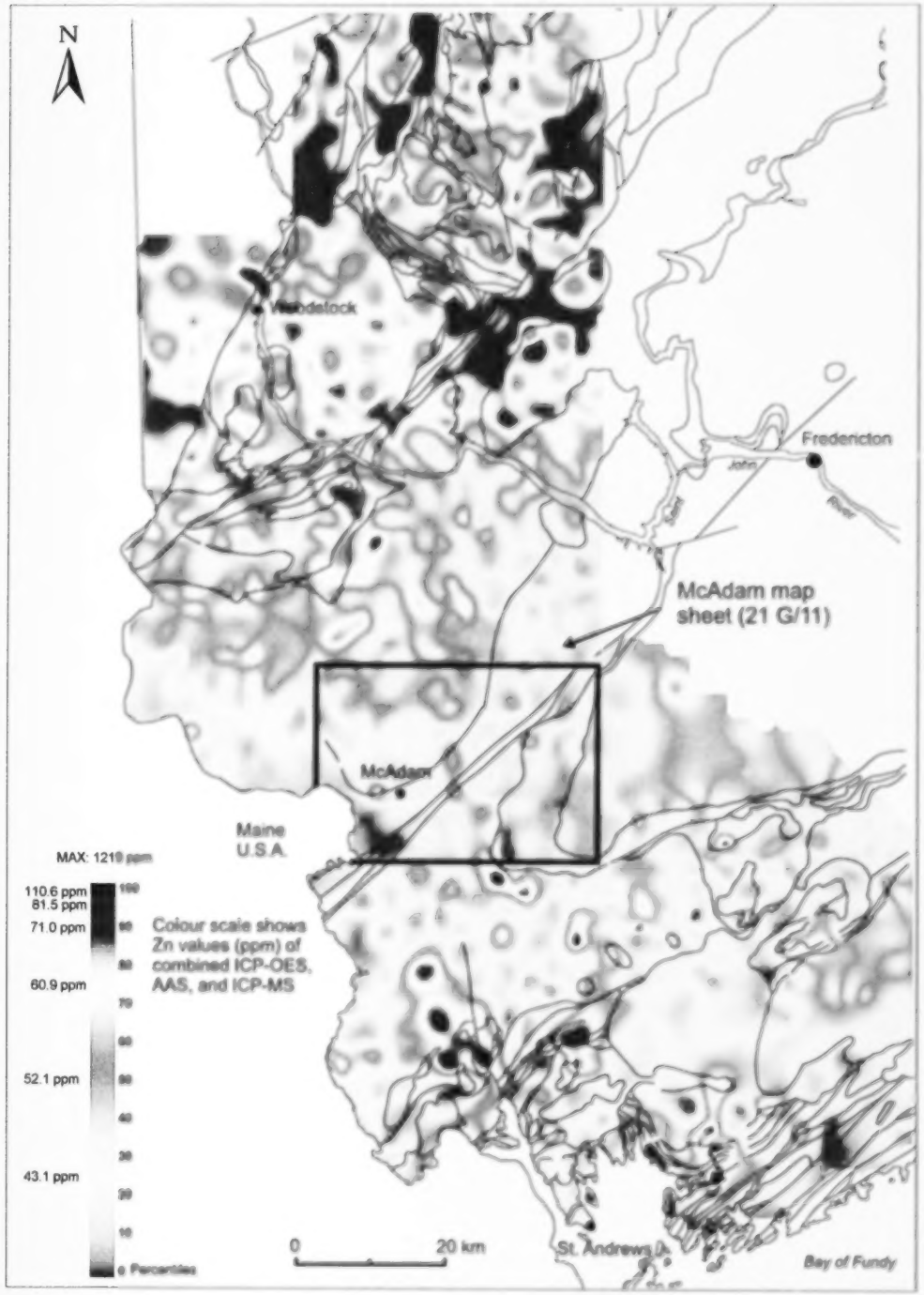

Figure 6. Unlevelled Zn contours. Data represent the combined ICP-OES, AAS, and ICP-MS values. Base map is taken from NR-1 (NBDNRE 2000), which provides names and descriptions of bedrock units outlined here in black.

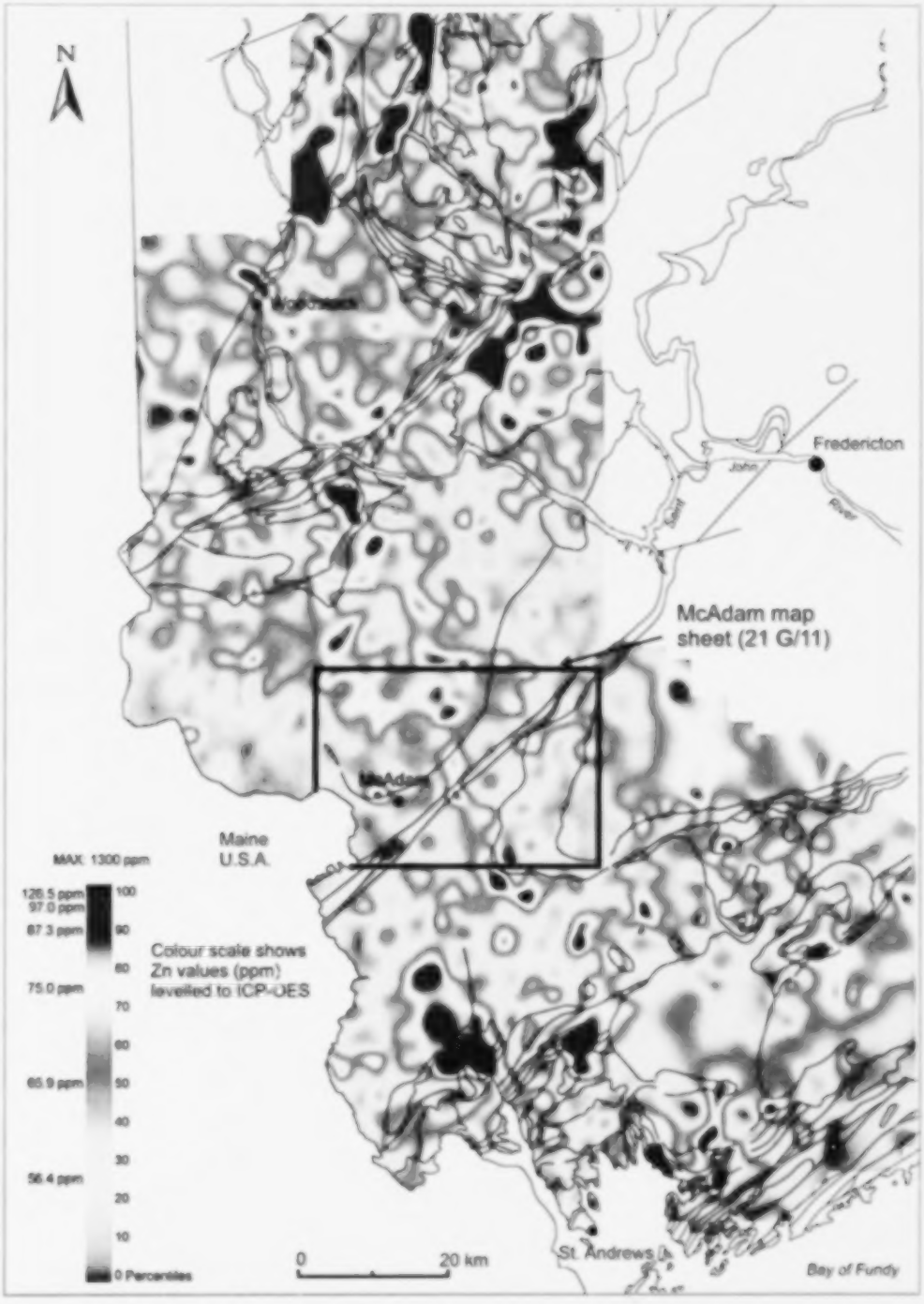

Figure 7. Levelled Zn contour plot. Data are levelled to ICP-OES. Base map is taken from NR-1 (DNRE 2000), which provides names and descriptions of bedrock units outlined here in black.

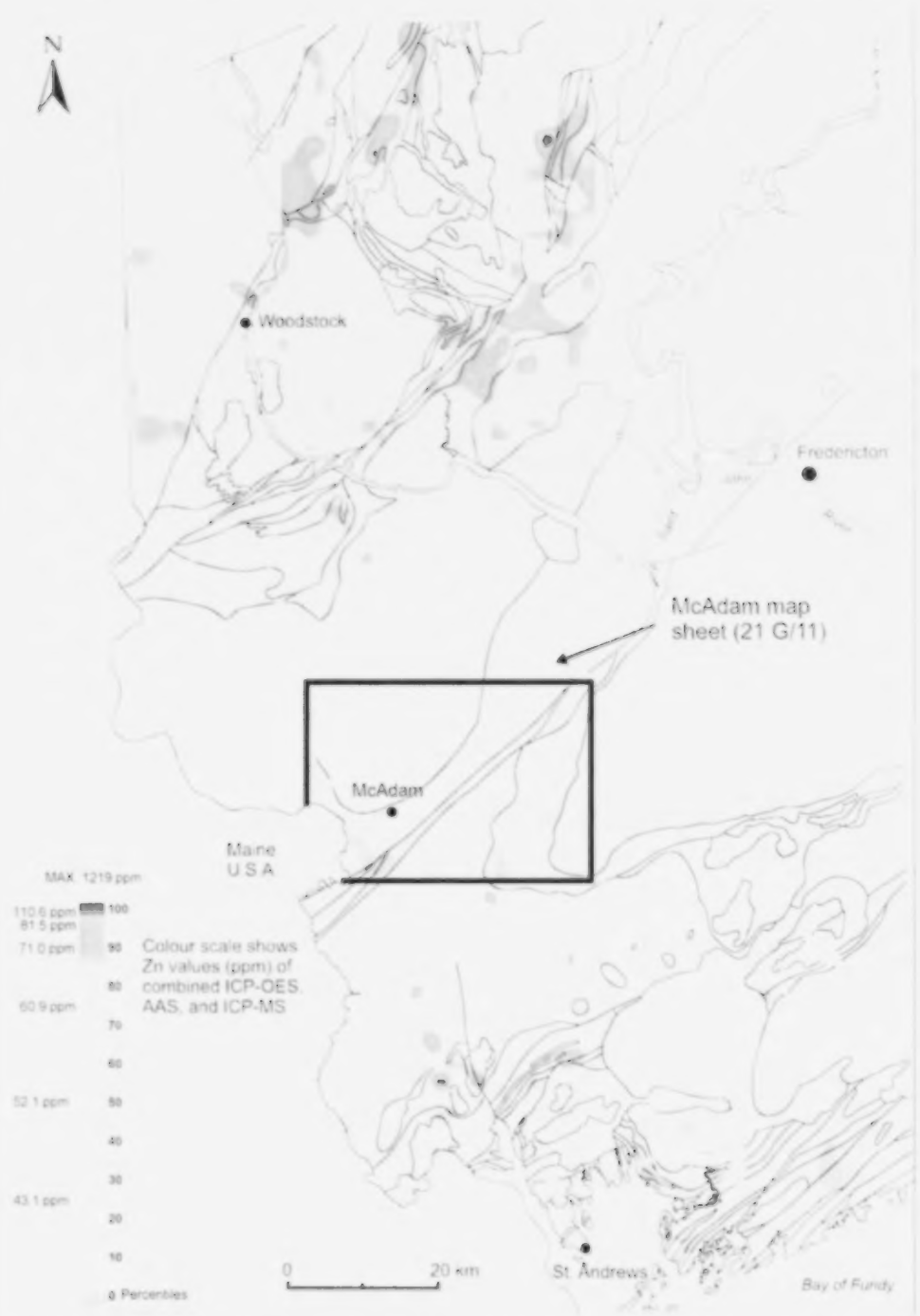

Figure 6. Unlevelled Zn contours. Data represent the combined ICP-OES, AAS, and ICP-MS values. Base map is taken from NR-1 (NBDNRE 2000), which provides names and descriptions of bedrock units outlined here in black.

Figure 7. Levelled Zn contour plot. Data are levelled to ICP-OES. Base map is taken from NR-1 (DNRE 2000), which provides names and descriptions of bedrock units outlined here in black.

CONCLUSIONS

Working with samples from southwestern New Brunswick, the author has successfully levelled 24 elements in till geochemistry data that had been analyzed using various analytical techniques and laboratories. The newly levelled data will be presented as regional-scale, colour contour maps in an upcoming DNR Mineral Resource Report and also will be made available as needed to compile regional contour plots for mineral exploration purposes. The report will include 1) detailed explanations of contouring techniques and interpretations, 2) a complete list of unit descriptions corresponding to the bedrock base map, and 3) interpretations of till geochemistry and glacial history in southwestern New Brunswick.

This work represents a pilot project for the levelling of till geochemistry data in New Brunswick — the first such levelling project of its kind ever conducted by the Department of Natural Resources. As the program evolves, techniques will be improved and adapted where applicable. The author, for example, already is considering the use of a weighted regression quantile normalization technique (*see* Daneshfar and Cameron 1998) to level geochemical data in southwestern New Brunswick. Unlike methods that rely on equal-weight linear regression, this technique allows more flexibility in terms of weighting specific, heavily populated quantiles.

The author offers the following recommendations and considerations for the improvement of data levelling in New Brunswick, based on his experience with this project.

Recommendations to Improve Data Levelling in Southwestern New Brunswick

1. An extraction of between ten and twenty ICP-MS survey samples, representing a wide range of concentrations, should be re-analyzed using ICP-OES, and vice versa. This would improve the reference set used in the levelling processes and thus improve the status of levelling ICP-OES with ICP-MS.

It also would be beneficial to produce more DNR standard reference materials data that better reflect the bedrock mineralogy of southwestern New Brunswick. This would facilitate greater precision in levelling between ICP-MS (AR digestion) and ICP-OES (4-acid digestion).

2. To improve consistency, an extraction of samples from surveys that used ICP-OES (AR digestion) should be re-analyzed using ICP-OES (4-acid digestion). This would give a better levelling base and provide insight into why the McAdam base-metal concentrations are anomalously low.

General Considerations

1. To minimize the need for future levelling, the diversity of analytical methods (including digestion conditions where applicable) and laboratories should be much reduced. A greater number of variables in a data set necessarily leads to increased complexity of the levelling process, which in turn yields less reliable levelled data.

2. Before beginning a regional or provincial levelling project, it may be beneficial to analyze ten samples from each 1:50 000-scale survey in a single run, using the technique to which the data will be levelled (such as INAA, ICP-MS or ICP-OES). This would provide a solid base line for parametric levelling.

3. Parametric normalization should be the preferred levelling method when working with adjacent surveys. Quantile regression techniques require the selection of data based on geographic location or bedrock characteristics. Conversely, parametric normalization is based solely on the comparison of reference data in the form of duplicates or standards. Parametric normalization yields excellent results, provided that it uses sufficient duplicate data representing a wide range of concentrations.

ACKNOWLEDGMENTS

Allen Seaman (DNR) and Robert Garrett from the Geological Survey of Canada (GSC) critically reviewed this paper, and Toon Pronk (DNR) approved it for publication. Eric Grunsky (GSC) deserves credit for providing the author with pertinent resources.

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PRE-MESOZOIC ROCKS OF GRAND MANAN ISLAND, NEW BRUNSWICK: FIELD RELATIONSHIPS, NEW U–PB AGES, AND PETROCHEMISTRY

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BLACK, R.S., BARR, S.M., FYFFE, L.R., and MILLER, B.V. 2004. Pre-Mesozoic rocks of Grand Manan Island, New Brunswick: Field relationships, new U–Pb ages, and petrochemistry. *In* Geological Investigations in New Brunswick for 2003. *Edited by* Gwen L. Martin. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division, Mineral Resource Report 2004-4, pp. 21–40.

Bedrock mapping and geochronological studies conducted during 2003 have led to a better understanding of stratigraphic relationships among pre-Mesozoic rocks on Grand Manan Island, New Brunswick. A sample from the High Duck Island Granite yielded a U–Pb zircon age of 547 ± 1 Ma. The granite intrudes strata of the Long Island Bay Formation, indicating that the minimum age of the formation is Late Neoproterozoic. A sample of dacitic lithic-crystal tuff from the Priest Cove Formation yielded a U–Pb zircon age of 539 ± 4.9 Ma, giving the formation an age of Early Cambrian. This date contradicts younger ages suggested previously on the basis of poorly documented fossil evidence. Preliminary geochemical data indicate that igneous rocks on the Grand Manan archipelago show wide chemical variation but are dominantly calc-alkaline, consistent with having formed in a volcanic-arc environment.

Les travaux de cartographie du substrat rocheux et les études géochronologiques réalisées au cours de 2003 ont permis de mieux comprendre les rapports stratigraphiques parmi les roches du Protérozoïque et du Paléozoïque sur l'île Grand Manan, au Nouveau-Brunswick. Le granite de l'île High Duck, qui fait intrusion dans des strates de la Formation de Long Island Bay, a été situé à 547 ± 1 Ma selon une datation à l'U–Pb obtenue à partir de zircon, ce qui fait remonter la Formation au Néoprotéozoïque tardif, au minimum. Une datation à l'U–Pb conférant un âge de 539 ± 4,9 Ma à du tuf cristallin dacitique, révèle que la Formation de Priest Cove remonte au Cambrien inférieur, ce qui entre en contradiction avec les datations les plus récentes antérieurement avancées d'après des indices fossiles peu documentés. Des données géochimiques préliminaires révèlent que les roches ignées de l'archipel de Grand Manan présentent une diversité de compositions chimiques, mais qu'elles sont en prédominance calco-alcalines, c'est-à-dire une composition correspondant à une constitution au sein d'un environnement d'arc volcanique.

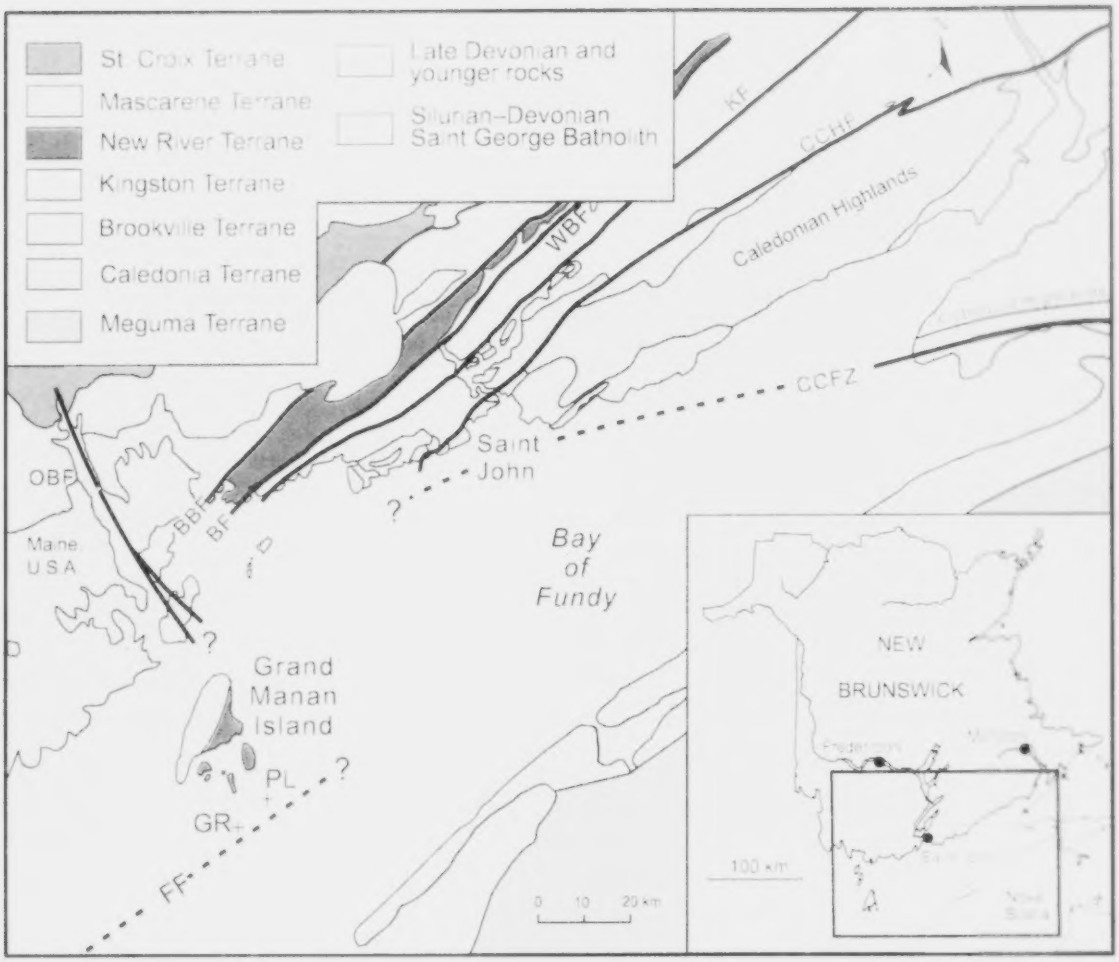
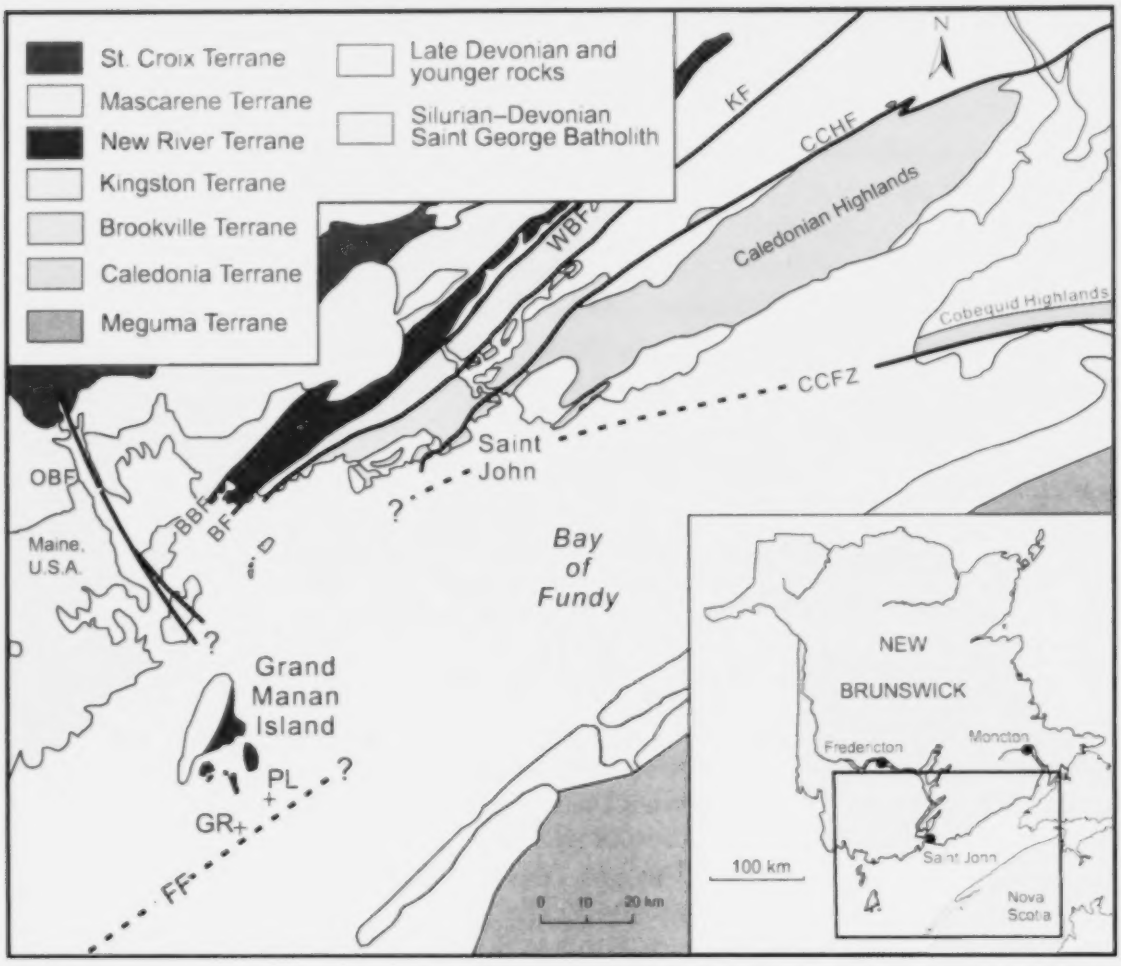


Figure 1. Grand Manan archipelago, southwestern Bay of Fundy. BBF = Back Bay Fault, BF = Belleisle Fault, CCFZ = Cobequid–Chedabucto Fault Zone, CCHF = Caledonia–Clover Hill Fault, FF = Fundy Fault, GR = Gannet Rock, KF = Kennebecasis Fault, OBF = Oak Bay Fault, PL = Proprietors Ledge, WBF = Wheaton Brook Fault.

Introduction

Grand Manan and surrounding islands in the southern Bay of Fundy lie strategically along strike of the southeasterly projection of the Oak Bay Fault and close to the inferred boundary between the Meguma and Avalon terranes (Fig. 1). The islands also are situated along strike of several terranes on mainland New Brunswick and Nova Scotia, and their possible counterparts in the northeastern United States. Hence, the Grand Manan archipelago is a key study area for establishing regional terrane correlations and insights into tectonic interactions between the Avalon and Meguma terranes.



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Previous correlations of Grand Manan Island with other areas in the Appalachian Orogen have been limited by insufficient petrological studies and age control. Presumed Lower Paleozoic rocks of the archipelago have been correlated with various units in Maine, New Brunswick, and Nova Scotia (Alcock 1948; Potter et al. 1979; McLeod et al. 1994; Pe-Piper and Wolde 2000; Fyffe and Grant 2000, 2001). This paper presents initial results from an M.Sc. thesis by the first author. Its purpose is to develop a detailed geological, petrological, and structural history of the Grand Manan archipelago and clarify its relationship to other areas of the northern Appalachian Orogen.

GEOLOGICAL SETTING

Rocks with peri-Gondwanan affinities in southern New Brunswick occur in roughly northeast-trending, fault-bound belts that are dissimilar in both age and composition (Fyffe and Fricker 1987; Barr and White 1996; Barr et al. 2002). From outboard to inboard, these belts have been named the Caledonia, Brookville, Kingston, New River, and Mascarene terranes (Fig. 1). The St. Croix and Miramichi terranes farther inland are larger and less linear than the five outboard terranes. Various interpretations exist of relationships among these terranes, but the Caledonia Terrane at least is generally considered part of the Avalon Terrane of the northern Appalachian Orogen (e.g. van Staal et al. 1998; Fyffe et al. 1999; Johnson 2001; Barr et al. 2003).

Studies indicate that the St. Croix, Mascarene, and Kingston terranes extend fairly continuously into eastern Maine, exhibiting only minor offset by the sinistral Oak Bay Fault system (Fyffe et al. 1999; McLeod et al. 2001). In contrast, the New River and Brookville terranes appear to be truncated by the fault. The Caledonia Terrane, which is bound on the north by the Caledonia–Clover Hill Fault, thins to the southwest, and is exposed onshore for only a few kilometres southwest of the City of Saint John (Fig. 1). In northern mainland Nova Scotia, the Cobequid–Chedabucto Fault separates the southern boundary of the Avalon Terrane from the Meguma Terrane to the south, and extends across the Bay of Fundy toward New Brunswick.

Deep seismic reflection profiles in the Bay of Fundy have been used to develop a model in which the Meguma Terrane was emplaced northwestwards over the Avalon Terrane along the Cobequid–Chedabucto and Fundy faults (Keen et al. 1991; Wade et al. 1996). This model was based partly on correlation between the oldest rocks on Grand Manan Island and an inferred basement to the Meguma Terrane, as possibly represented by the Liscomb Complex in the northern part of the Meguma Terrane. Keen et al. (1991) also proposed an alternate model, whereby rocks beneath Grand Manan Island belong to the Avalon Terrane and were thrust eastwards over the Meguma Terrane. Other workers have correlated Grand Manan Island with the New River Terrane in southern New Brunswick (Pe-Piper and Wolde 2000), the 'Mispec Group' near Saint John (Stringer and Pajari 1981), or the Coldbrook, Green Head, and Broad River groups of the Caledonia and Brookville terranes (Alcock 1948; Fyffe and Grant 2000).

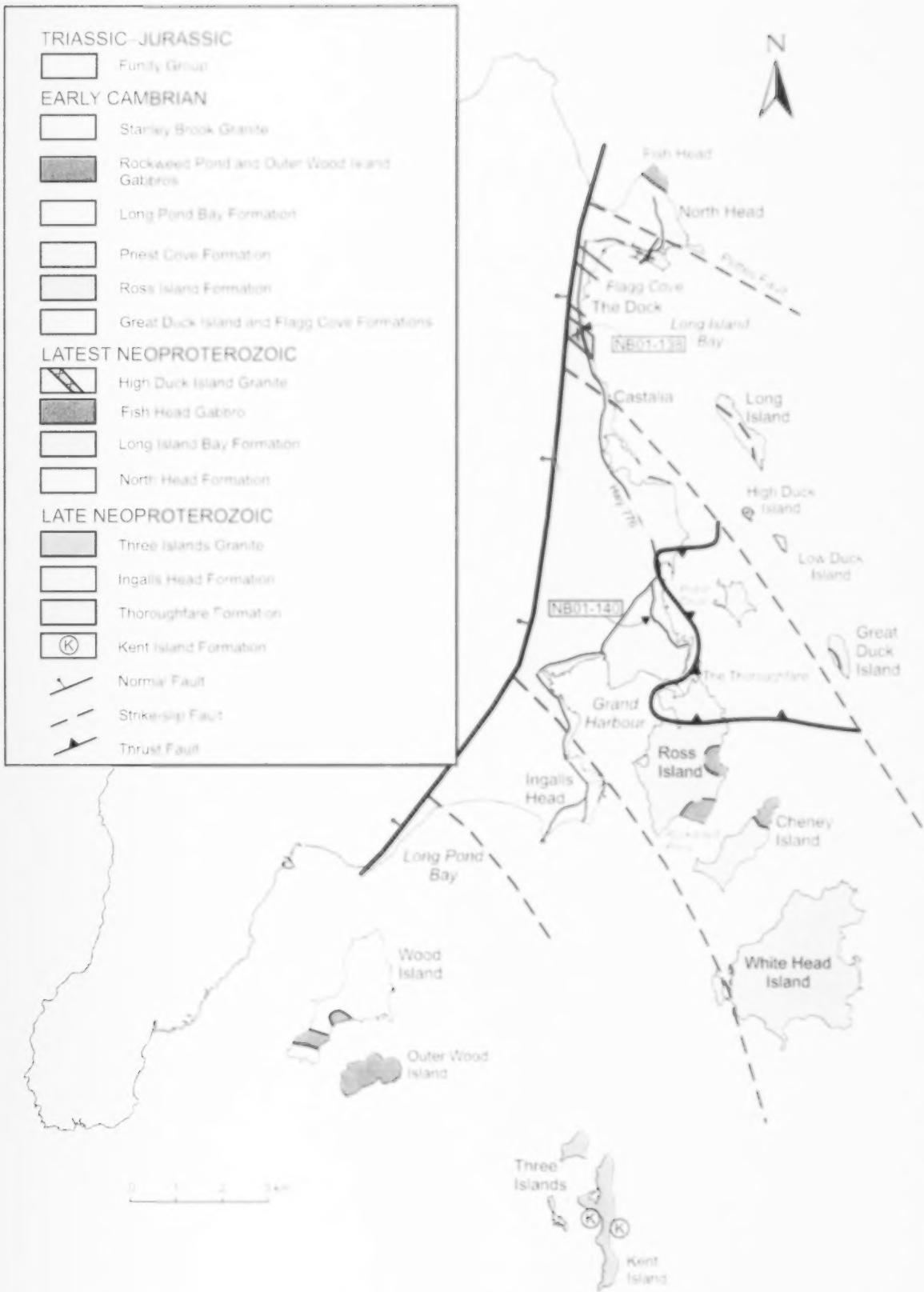

Figure 2. Geology of eastern Grand Manan Island and surrounding islands, based on present study.

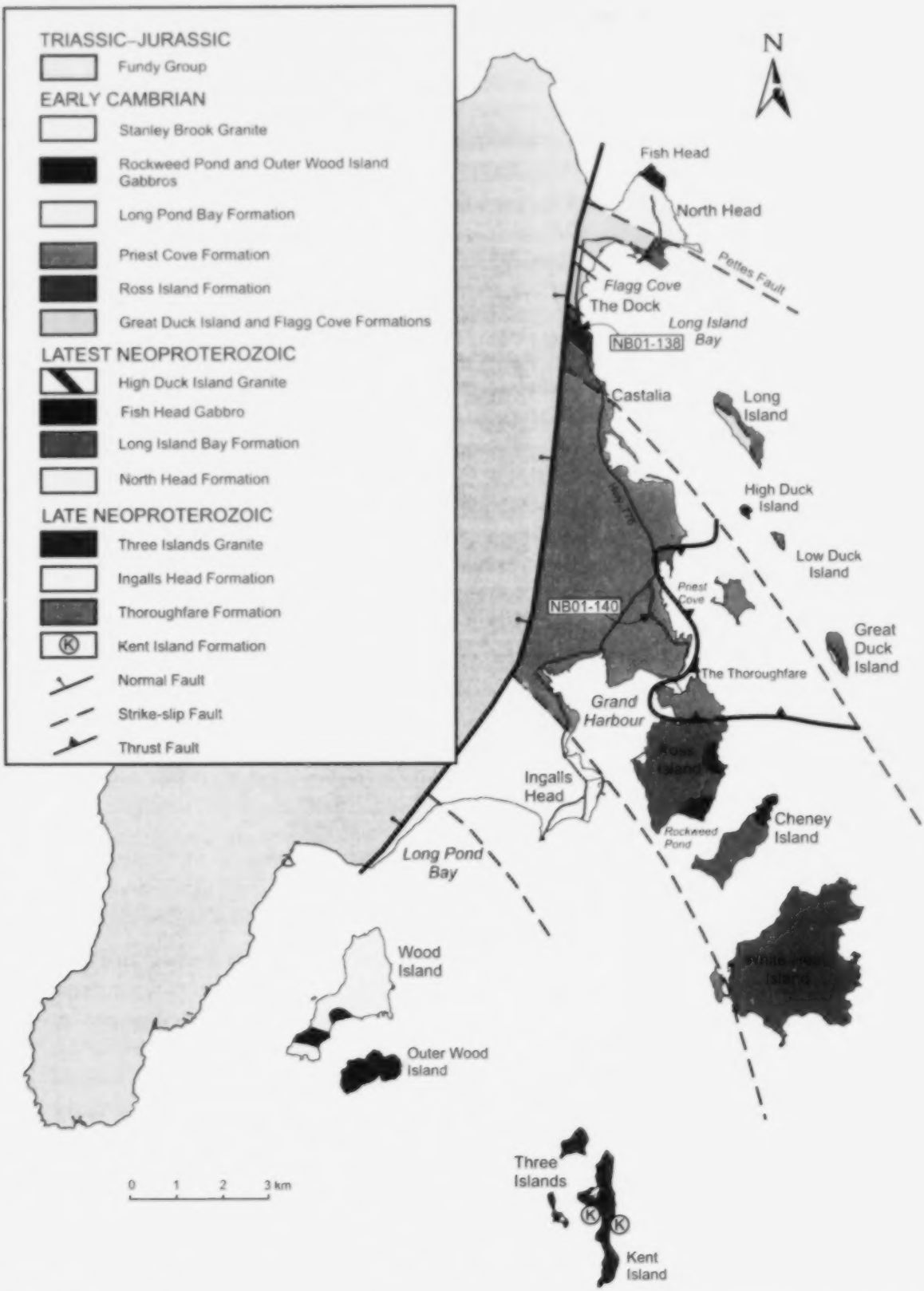

Figure 2. Geology of eastern Grand Manan Island and surrounding islands, based on present study.

Geology of Grand Manan Island

Pre-Mesozoic rocks underlying Grand Manan Island are exposed in the footwall of a post-Jurassic normal fault (Fig. 2). The hanging wall comprises Late Triassic to Early Jurassic basaltic flows and minor redbeds of the Fundy Group (Fyffe and Grant 2000, 2001). Footwall rocks are complexly folded and faulted, and in places display three or more cleavages. Contacts between formations generally are covered, but cataclastic shear in adjacent units suggests the presence of late, brittle faults (Fig. 2).

The pre-Mesozoic stratified units consist mainly of volcanic and volcaniclastic rocks, and quartz-rich sedimentary rocks. Map units are divided on the basis of differences in the dominant rock type present, inferred depositional environment and/or apparent differences in structural histories, and U–Pb zircon ages. Unit terminology generally follows that of Fyffe and Grant (2000, 2001) but is modified by results of the current work. Primary sedimentary and igneous features are well preserved in many places, and metamorphic grade generally does not exceed greenschist facies.

The oldest unit on the Grand Manan archipelago is medium-grained, bright white to buff marble of the Kent Island Formation. Its only known occurrence is as large xenoliths in the ca. 611 Ma Neoproterozoic Three Islands Granite on the west and east sides of Kent Island (Fig. 2). Small exposures of steely grey magnetite skarn also are visible at low tide. The relationship of the marble and skarn to other stratigraphic units is uncertain; however, rare marble and abundant quartzite clasts are found in a cobble conglomerate that forms the entire Gannet Rock south of Grand Manan Island (Fig. 1). These clasts may have been derived from the Kent Island and Thoroughfare formations, which implies that the formations could be of similar age.

The Thoroughfare Formation is composed predominantly of intercalated, light grey, thin- to medium-bedded quartzite, sideritic siltstone and black carbonaceous chloritoid schist (Fig. 3), and overlying thick-bedded to massive quartzite. The Thoroughfare Formation is interpreted to occur in a klippe. The klippe also includes small amounts of overlying greyish-green clastic sedimentary rocks and light grey felsic tuff that are considered part of the Ingalls Head Formation (Fig. 2). The relative age of these two formations is inferred from the presence of white quartzite pebbles in clastic units of the Ingalls Head Formation in the southern part of the Ingalls Head coastal section. These pebbles appear to have been derived from the Thoroughfare Formation.

The Ingalls Head Formation is the oldest reliably dated unit on Grand Manan Island. Felsic tuff from the unit yielded a U–Pb zircon age of 618 ± 3 Ma (Barr et al. 2003). Most rocks assigned to this formation occur near Ingalls Head and on scattered offshore islands. The rocks consist of felsic

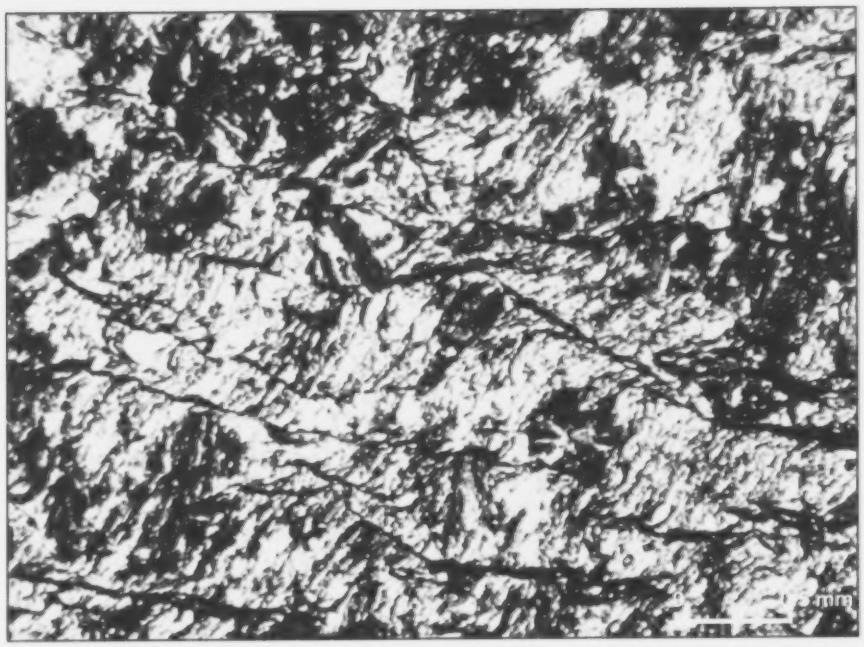

Figure 3. Photomicrograph of carbonaceous chloritoid schist from the Thoroughfare Formation. Plane polarized light.

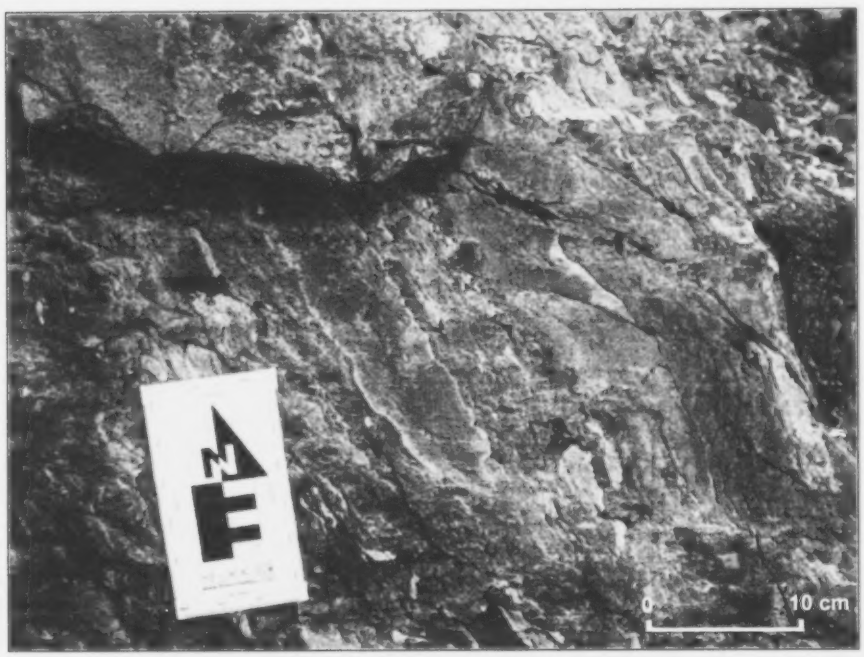

Figure 4. Dacitic volcanic breccia in the Ingalls Head Formation. Clasts exhibit at least three cleavages and a white reaction rim that presumably was caused by reaction with the surrounding volcanic material.

to mafic flows and tuff, green and purple laminated mudstone, and volcanic breccia (Fig. 4). Rocks on Ingalls Head appear as a synform; its core is dominated by mafic to intermediate tuff, and its limbs are composed of felsic tuff, volcanic breccia, and mudstone. The mudstone units have locally high magnetic susceptibilities, indicating magnetite concentrations that are sufficient for some units to be classified as ironstone. The Ingalls Head Formation can be traced offshore using its strong magnetic signature (Oakey and Dehler 2003), which presumably is caused by the magnetite-rich mudstone. The 611 ± 3 Ma Three Islands Granite likely is related to the Ingalls Head Formation, as evidenced by their similar ages.

The newly defined Long Island Bay Formation consists of thick-bedded, greyish-green volcaniclastic rocks, plagioclase-phyric basaltic flows, light grey felsic lithic tuff, and siderite-chloritoid-bearing green and maroon siltstone. An unconformity separates these rocks from thin-bedded quartzite, siderite-bearing grey siltstone, and black shale of the Flagg Cove Formation. The unconformity is marked by a pebble to cobble conglomerate of the Great Duck Island Formation, containing clasts of basalt, quartzite, and siltstone (Fyffe and Grant 2000). This medium- to thick-bedded conglomerate unit truncates crystal-rich, plagioclase-phyric basaltic flows of the underlying Long Island Bay Formation at a high angle. On Long and Great Duck islands, the conglomerate also contains volcanic clasts derived from these flows (Fig. 5). The conglomerate is interpreted as being correlative to the maroon and green volcanic- and quartz-pebble conglomerate exposed at The Dock in Long Island Bay (Fyffe and Grant 2000).

The Long Island Bay, Great Duck, and Flagg Cove formations show evidence of several deformational events. Greenschist-facies metamorphism is indicated by pre- to syntectonic, euhedral, chloritoid porphyroblasts up to 1 mm in diameter. The High Duck Island Granite intrudes maroon siltstone of the Long Island Bay Formation south of The Dock (Fig. 2) and also is found on High Duck Island. The High Duck Island Granite has yielded a new U–Pb zircon age of 547 ± 1 Ma, which indicates a minimum age of Late Neoproterozoic for the Long Island Bay Formation (*see* GEOCHRONOLOGY). Volcanic rocks of the Long Island Bay Formation are assumed to be comagmatic with the High Duck Island Granite (*see* GEOCHEMISTRY) and thus to be younger than the Ingalls Head Formation.

North of The Dock, the ca. 535 Ma Stanley Brook Granite (van Staal et al. 2004) intrudes grey siltstone and pebble conglomerate of the Flagg Cove Formation (Fig. 2), which implies a minimum age of Early Cambrian for that formation. The same granite is seen on Long Island, where it intrudes chloritoid-bearing grey sandstone. The sandstone is assigned to the Flagg Cove Formation, based on its compositional similarity to rocks placed in the formation elsewhere and its association with the Stanley Brook Granite.

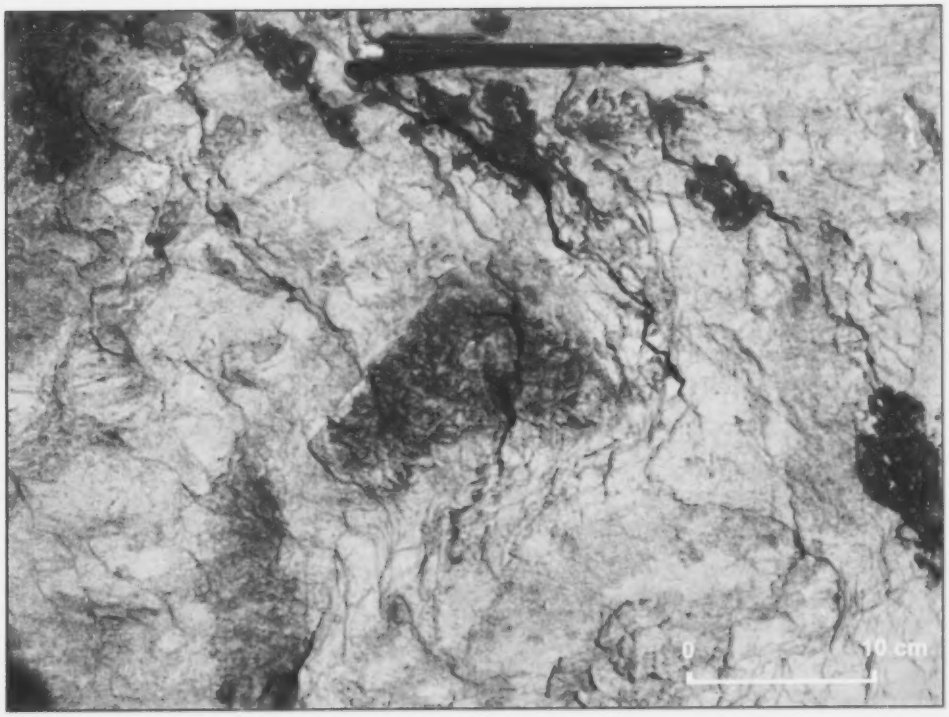

Figure 5. Basal conglomerate of the Great Duck Island Formation on Long Island, containing plagioclase-phyric basalt clasts from the underlying Long Island Bay Formation.

The Priest Cove, Ross Island, and Long Pond Bay formations are composed of relatively uncleaved mafic to intermediate volcanic rocks, and reworked volcaniclastic rocks. In addition to these formations, for which a stratigraphic position can be inferred, a separate package of volcanic rocks named the North Head Formation occurs on the northeastern tip of Grand Manan Island. The Pettes Fault separates these latter rocks from the other units (Fig. 2). Cleavages interpreted as being associated with the Pettes Fault are steep to vertical, implying strike-slip motion along the fault.

The Priest Cove Formation includes coarse- to fine-grained mafic volcaniclastic sandstone, siltstone, and intermediate crystal-lithic lapilli tuff. Metamorphic grade generally is low, and original sedimentary features typically are preserved. A dacitic lithic-crystal tuff near the central part of the formation yielded a U–Pb zircon age of ca. 539 Ma (*see* GEOCHRONOLOGY), indicating that the age of the formation is earliest Cambrian. This age contradicts the age based on a poorly documented Silurian fossil assemblage that included brachiopod, echinoderm, and mollusc fragments (Hilyard 1992).

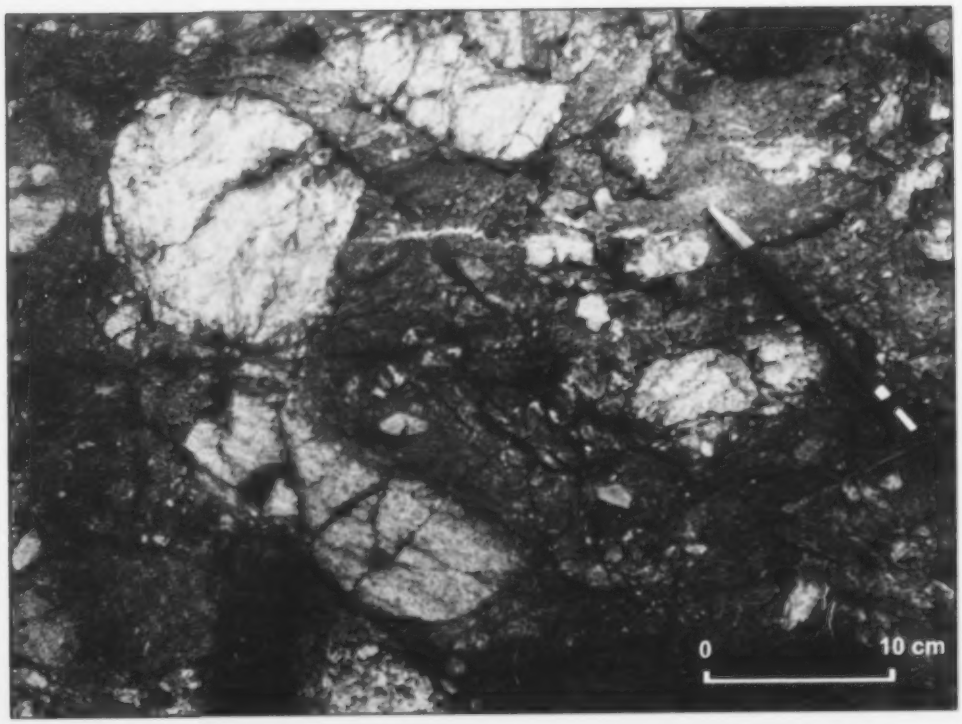

Figure 6. Conglomerate containing granite and quartzite clasts at base of the Ross Island Formation.

The Ross Island Formation is characterized by a thick sequence of mafic flows locally interbedded with pillow basalt, basaltic breccia, chert, and laminated siltstone. These subaqueous, mainly eruptive rocks may in part be a lateral facies equivalent of mafic volcaniclastic rocks of the Priest Cove Formation (Stringer and Pajari 1981). Thin-bedded, fine-grained, greyish-green wacke and siltstone form a substantial component of the Ross Island Formation on the western parts of White Head and Ross islands. These strata are inferred to lie toward the base of the Ross Island Formation. The poorly rounded feldspar clasts in these rocks suggest that they were formed by moderate reworking of material derived from nearby mafic volcanic centres. Similar sedimentary rocks are found westwards along strike in Grand Harbour on Grand Manan Island. These rocks appear to be overlain by mafic volcaniclastic rocks of the Priest Cove Formation, as evidenced by the presence of graded bedding.

A distinctive conglomerate associated with peperitic basalt at the base of the Ross Island Formation contains cobble- to boulder-sized clasts of granite, granitic pegmatite, and micaceous white quartzite (Fig. 6). It also features large muscovite booklets set in a matrix of dark green muscovite and chlorite. Granite clasts from the conglomerate yielded K–Ar muscovite ages of 640 Ma and 590 Ma (Leech et al. 1963; Lowdon et al. 1963), or 650 Ma and 600 Ma as recalculated by

Stringer and Pajari (1981). The conglomerate is interpreted as recording the deposition of detritus from an advancing fault scarp dominated by rocks of the older Ingalls Head and Thoroughfare formations. The Rockweed Pond Gabbro exposed on Ross Island is closely associated, and likely cogenetic, with volcanic rocks of the Ross Island Formation. The Proprietors Ledge Gabbro is situated 15 km south of Ross Island. Its location and petrographic similarities to the Rockweed Pond Gabbro suggest that the two intrusions may be related.

The Long Pond Bay Formation on Long Pond Bay (Fig. 2) consists of subaqueous hyaloclastic basalt flows, mafic volcanic breccia, peperitic basalt, green cherty mudstone, and medium- to thick-bedded wacke. Hematite-stained amygdaloidal basalt flows, felsic tuff, and arkosic sandstone can be seen on Wood Island and appear to have been deposited in shallower water. These rocks also are included in the Long Pond Bay Formation (Fyffe and Grant 2001). The presence of relict pyroxene and zeolite-filled amygdales indicates that the rocks have not been metamorphosed beyond upper zeolite to lowest greenschist facies. Neither fossil nor radiometric evidence have yet been obtained to date the formation. Nonetheless, its weak metamorphism and minimal deformation (other than soft-sediment) relative to other units in the area together suggest that the formation comprises the youngest pre-Mesozoic rocks exposed on the Grand Manan archipelago. The Long Pond Bay Formation is intruded by the fine- to medium-grained Outer Wood Island Gabbro, which lies beneath all Outer Wood Island and likely was emplaced into the shallow-water to subaerial clastic rocks exposed on Wood Island.

The North Head Formation consists of massive, thick-bedded mafic flows and breccia, and intermediate lithic-crystal tuff. Two medium- to coarse-grained layered gabbro bodies intrude, and are likely are cogenetic with, the volcanic rocks (*see* GEOCHEMISTRY). The breccias locally contain epidotized bombs up to 20 cm in diameter. The volcanic rocks and gabbro display cleavages similar in orientation to those of the Long Island Bay Formation. As well, the gabbro has undergone greenschist-facies metamorphism, as evidenced by abundant amphibole, biotite, epidote, and chlorite, and absent relict pyroxene. This contrasts with gabbro from the Ross Island and Long Pond Bay formations, in which the original clinopyroxene remains. Hence, the North Head Formation and associated Fish Head Gabbro are interpreted as being older than those units, and latest Neoproterozoic in age (Fig. 2).

GEOCHRONOLOGY

Barr et al. (2003) and van Staal et al. (2004) previously reported U–Pb ages of samples from the Grand Manan archipelago. The present study provides new U–Pb ages of two additional samples: granite from the High Duck Island Granite, which intruded the Long Island Bay Formation, and dacite lithic-crystal tuff from the Priest Cove Formation. Analytical methods used were similar to those described in Barr et al. (2003).

High Duck Island Granite

The dated sample of High Duck Island Granite (NB01-138) comes from the shore of Long Island Bay south of The Dock (Fig. 2). This tan-weathering, greenish-pink granite is fractured and fine grained. The rock is pervasively saussuritized and moderately porphyritic, consisting of euhedral plagioclase crystals set in a granophyric groundmass of plagioclase, alkali feldspar, and quartz. The sample contains two morphologies of prismatic zircon grains. The more prevalent type comprises small, simple tetragonal zircon grains that typically include both dark and clear mineral inclusions. The second type consists of rare, moderately large, clear acicular zircon grains.

The ten selected fractions consisted of five single grains (four of which contained an inherited component) plus five fractions consisting of small prismatic zircon grains or their broken tips. As shown on the concordia diagram (Fig. 7a), one batch of five small prismatic zircon grains was nearly concordant at about 580 Ma and anchored a poorly defined array of analyses that may represent mixing between the ca. 580 Ma and ca. 2800 Ma components. (Conversely, the alignment may be coincidental.) The five remaining fractions comprised batches of two to five small prismatic grains, a batch of three grain tips, and one fairly large, clear acicular prism. All five analyses were concordant and yielded a mean concordia age (Ludwig 1989) of 547.3 ± 1.1 Ma. We interpret this latest Late Neoproterozoic date as the time of granitic intrusion. Given the high emplacement level of the granite, as revealed by its granophyric texture, the date also may approximate the age of the Long Island Bay Formation.

Priest Cove Formation

The dated sample of Priest Cove Formation (NB01-140) is from a dacitic lithic-crystal tuff exposed along the Shore Road (Fig. 2). It contains abundant subhedral to euhedral crystal fragments of plagioclase, alkali feldspar, and quartz less than 2 mm in diameter. The fragments are set in a mineralogically similar, fine-grained groundmass containing epidote and abundant opaque minerals. Crystal fragments are moderately saussuritized and locally display resorption textures. Lithic fragments usually are less than 2 mm in diameter. Most are volcanic in origin and consist of euhedral plagioclase laths, alkali feldspar, and quartz. Rare, large lithic fragments are composed of fine-grained volcaniclastic sandstone.

Zircon grains from this sample were either small tetragonal prisms with common mineral inclusions or large, clear, partly rounded grains. We interpreted the latter grains as inherited xenocrysts and thus focused attention on the former morphology, which in our experience is more typical of phenocrystic zircons. Six fractions containing either one or two grains were selected on the basis of their crystal form and having the fewest inclusions. All six fractions formed a discordant trend (MSWD = 1.02) showing an upper intercept of 539 ± 3.3 Ma (Fig. 7b). We consider the upper intercept to represent the eruption time for the volcanic component of the Priest Cove Formation, and to closely approximate deposition time of the formation.

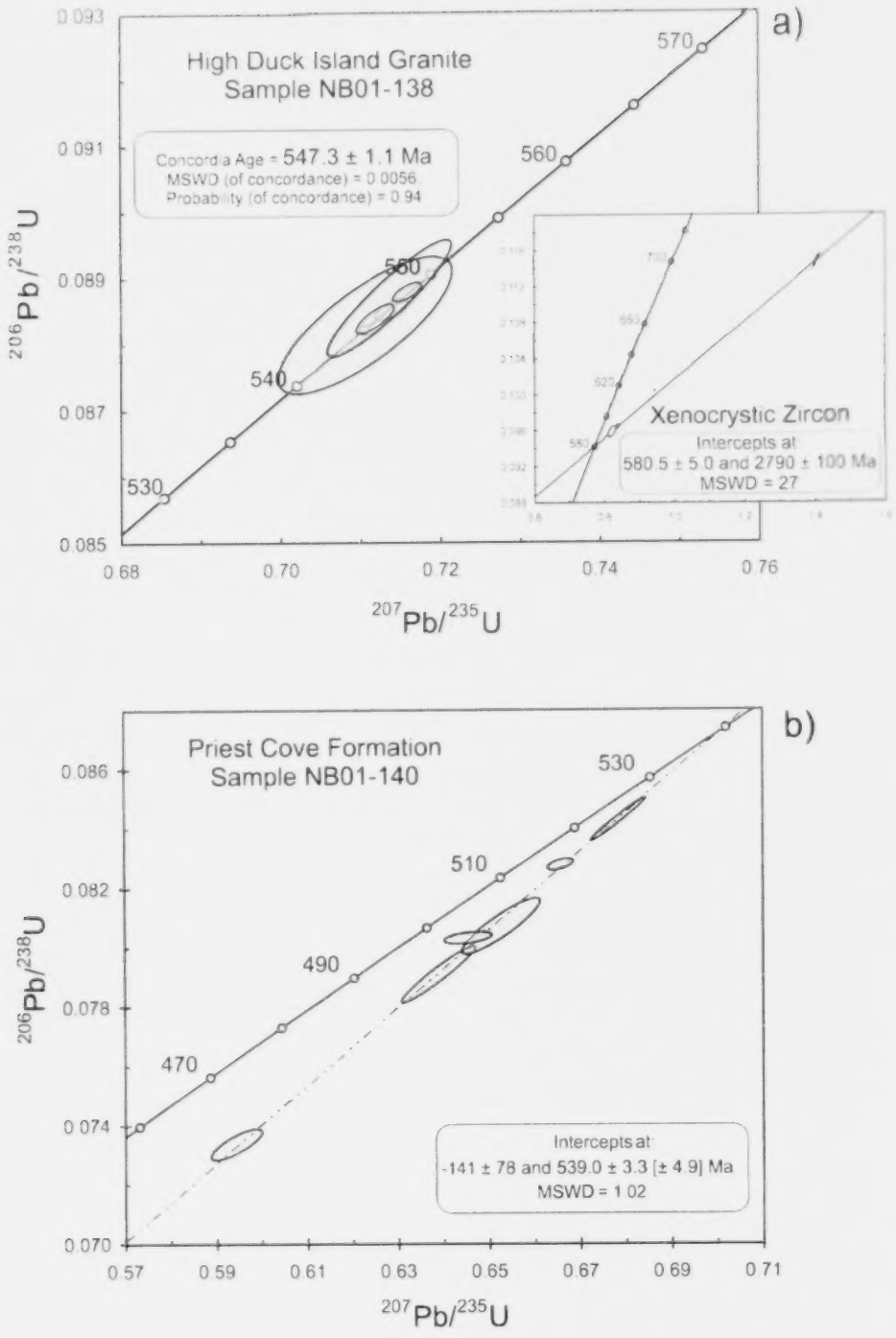

Figure 7. Concordia diagrams for age-dated samples from Grand Manan Island. a) High Duck Island Granite (NB01-138). b) Priest Cove Formation dacite (NB01-140).

GEOCHEMISTRY

As part of the present study, whole-rock major-element and trace-element analyses were obtained from forty samples representing pre-Mesozoic igneous units in the Grand Manan archipelago. The chemical data were plotted on various diagrams together with data from igneous units reported by Pe-Piper and Wolde (2000).

Samples of the Ingalls Head Formation are intermediate to felsic and show a wide range in immobile elements such as Zr, Nb, and Y (Fig. 8). In contrast, samples of the Long Island Bay Formation are mafic to intermediate in composition. Intermediate (60–70 wt % SiO_2) samples of the Long Island Bay Formation show several differences, such as lower TiO_2, when compared with intermediate samples of the Ingalls Head Formation. Samples from both formations, however, display broad variation in immobile elements such as Zr, Nb, and Y.

Samples of the Ross Island Formation are basaltic to andesitic (50–60 wt % SiO_2). They show a wide range in immobile element concentrations, especially TiO_2 and Nb (Fig. 8a, c), and many samples have high P_2O_5 (Fig. 8c). Unlike other volcanic units in the area, the Long Pond Bay Formation is bimodal, consisting of basalt and rhyolite. Basalt samples show lower P_2O_5, Zr, and Nb than do basalts of the Ingalls Head and Long Island Bay formations. The North Head Formation sample generally is similar in composition to mafic samples from the Long Pond Bay Formation. The single Priest Cove Formation sample is dacitic and shows lower Zr, Nb, and Y than do samples with similar SiO_2 content from other units (Fig. 8).

The presumed cogenetic relationship between gabbroic bodies and their volcanic hosts in the Grand Manan area is supported by the chemical data, particularly the concentrations of immobile elements (Fig. 8). For example, analyses from both the Outer Wood Island Gabbro and Long Pond Bay Formation generally exhibit lower values of TiO_2, P_2O_5, Zr, and Nb than do analyses from the Rockweed Pond Gabbro and Ross Island Formation. A massive mafic dyke that intrudes highly deformed volcanic rocks of the Ingalls Head Formation shows chemical similarities to mafic volcanic rocks of the Ross Island Formation, indicating that the host rocks in this case are not cogenetic with the intrusion.

The Three Islands Granite has a higher SiO_2 content of about 75 wt % and displays elevated Nb and Y values, when compared with felsic samples from other units (Fig. 8). The High Duck Island Granite has a lower SiO_2 content of less than 70 wt %. It is chemically similar to, and may be comagmatic with, the dacite sample of the Long Island Bay Formation. No samples of the Stanley Brook Granite were analyzed because the rock is too altered and intermixed with dioritic rocks. A granitic clast from the conglomerate of the Ross Island Formation has a SiO_2 content similar to that

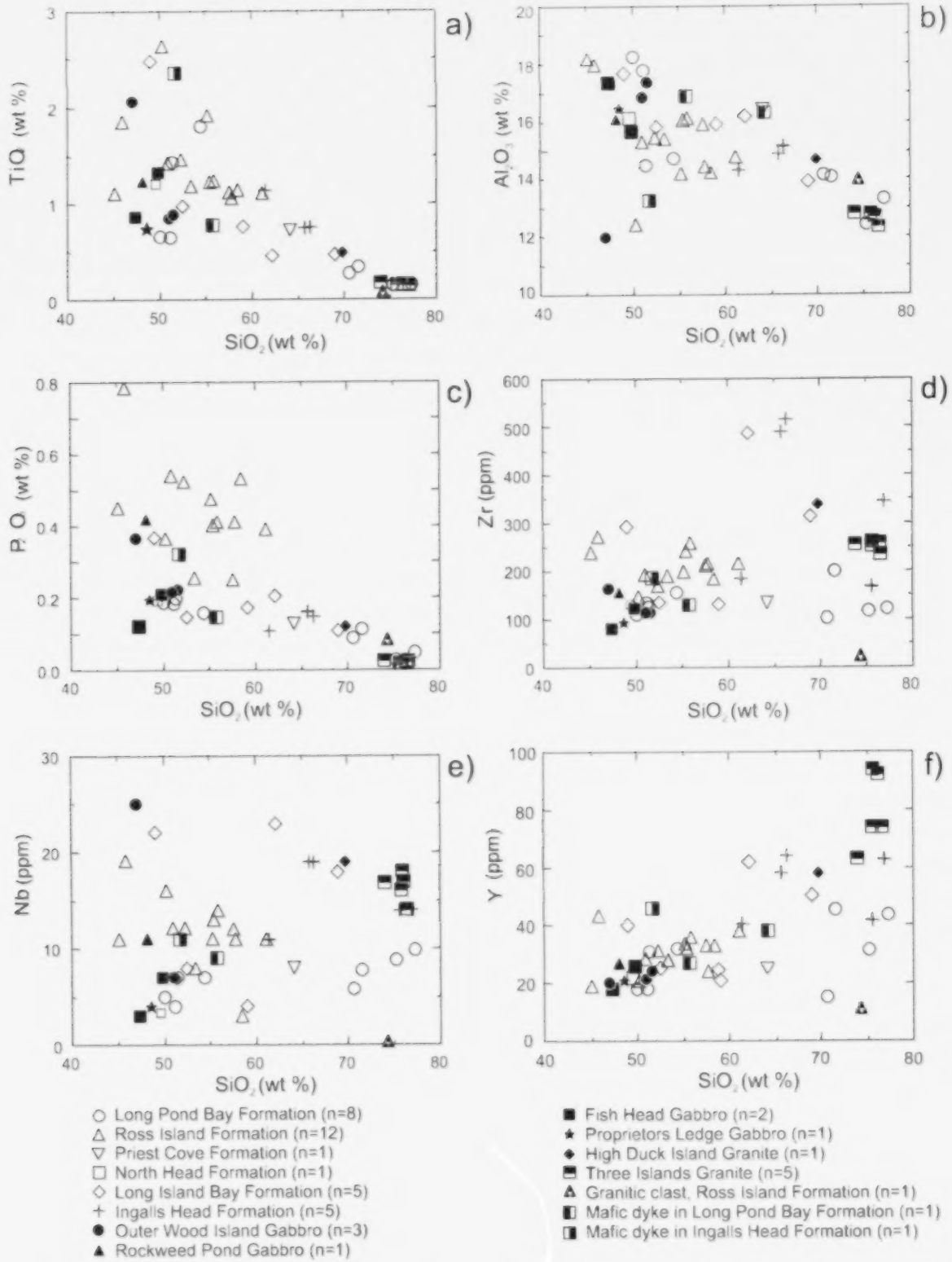

Figure 8. Selected Harker variation diagrams for pre-Mesozoic igneous rocks from Grand Manan Island and surrounding islands. Data on diagrams are from present study and Pe-Piper and Wolde (2000).

of the Three Islands Granite. In other respects it differs markedly, having higher Al_2O_3 and P_2O_5, and lower Zr, Nb, and Y (Fig. 8).

Most samples of volcanic and intrusive rocks from the Grand Manan archipelago plot in the subalkalic field, based on their Nb–Y ratio (Fig. 9a), and the calc-alkaline rather than tholeiitic field, based on the AFM diagram (Fig. 9b). Intermediate and felsic samples (SiO_2 >60 wt %) appear to be transitional between the volcanic-arc and within-plate fields (Fig. 9c). The High Duck Island and Three Islands granites show distinct within-plate characteristics (Fig. 9c). Mafic to intermediate samples (SiO_2<60 wt %) plot mainly in the calc-alkalic field on the Ti–Zr–Y ternary discrimination diagram (Fig. 9d), but appear more within-plate tholeiitic on the Ti–V diagram (Fig. 9e).

Conclusions and Future Work

The oldest Late Neoproterozoic rocks underlying the Grand Manan archipelago include a lower sedimentary assemblage (Kent Island and Thoroughfare formations), and an upper volcanic assemblage associated with cogenetic plutonic rocks (Ingalls Head Formation and Three Islands Granite). The older rocks lie in faulted contact with latest Late Neoproterozoic volcanic and cogenetic plutonic rocks (Long Island Bay Formation and High Duck Island Granite). The younger sequence is unconformably overlain by a varied assemblage of Early Cambrian sedimentary and volcanic rocks (Great Duck Island, Flagg Cove, Priest Cove, Ross Island, and Long Pond Bay formations, and possibly the North Head Formation). The sedimentary Flagg Cove Formation is intruded by the Cambrian Stanley Brook Granite.

Preliminary geochemical results indicate that the Ingalls Head Formation likely is cogenetic with the Three Islands Granite, which underlies offshore islands south of Grand Manan Island. Geochemical results also suggest that the various gabbroic bodies (Fish Head, Rockweed Pond, Outer Wood Island, and Proprietors Ledge) intrude cogenetic volcanic units, those being the North Head, Ross Island, and Long Pond Bay formations. The mainly calc-alkaline characteristics of the volcanic and mafic plutonic units are most consistent with a volcanic-arc tectonic setting; however, the granitic rocks exhibit within-plate affinities, perhaps as a result of their highly fractionated nature.

It remains difficult to correlate Proterozoic and Paleozoic units on Grand Manan Island with those on the mainland of southern New Brunswick. Marble and quartzite of the Kent Island and Thoroughfare formations, respectively, may be correlative with marble and quartzite from the Green Head Group of the Brookville Terrane, as first suggested by Alcock (1948). The Ingalls Head Formation is similar in age and some lithologic components to the ca. 620 Ma Broad River Group of the Caledonia Terrane (Barr and White 1999). The rock types and ages of the Long Island Bay,

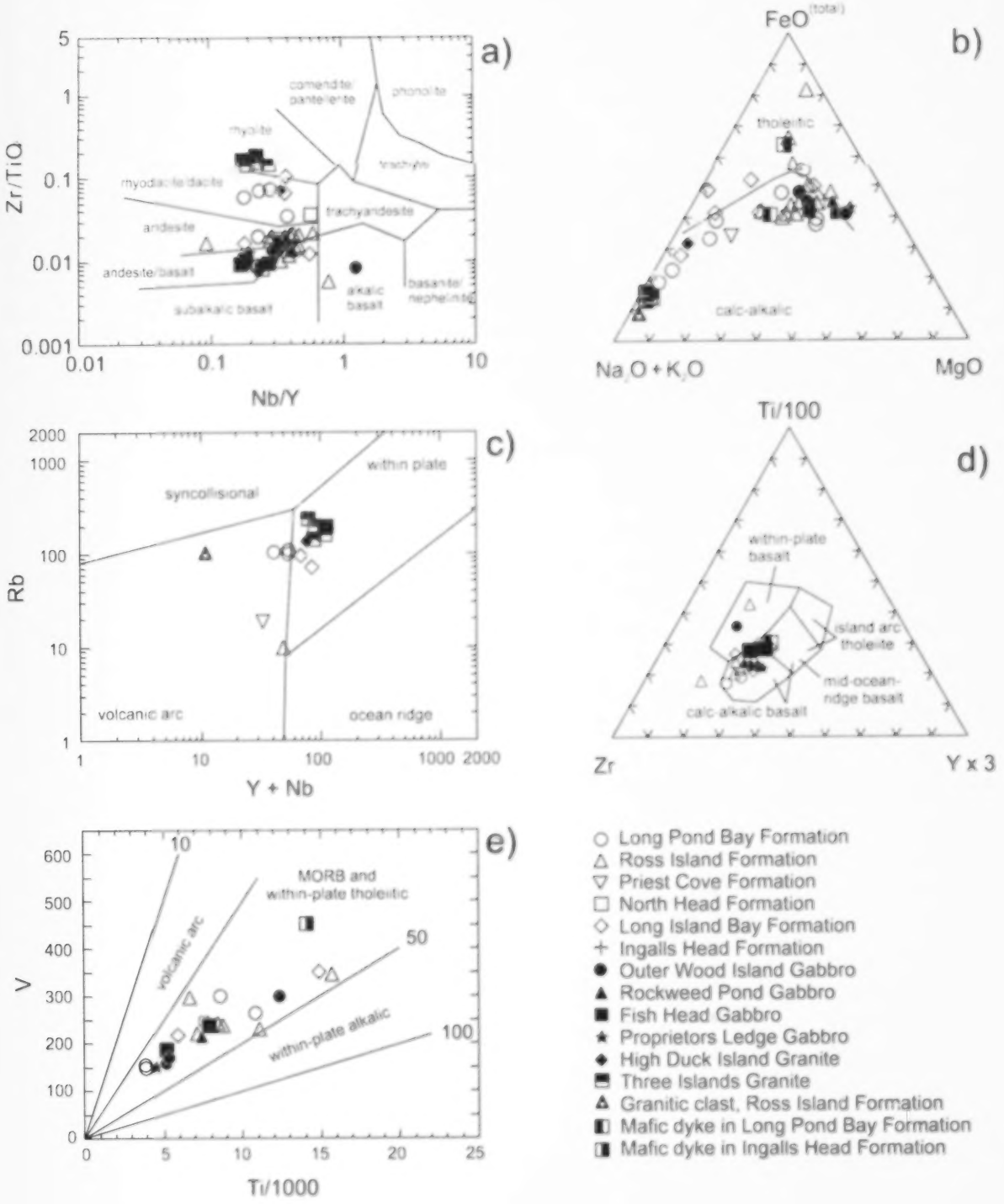

Figure 9. Discrimination diagrams for igneous rocks from Grand Manan Island and surrounding islands.
a) Zr/TiO_2 vs Nb/Y discrimination diagram from Winchester and Floyd (1977).
b) AFM discrimination diagram after Irvine and Baragar (1971).
c) Tectonic discrimination diagram for intermediate to felsic samples (SiO_2 >60%); fields from Pearce et al. (1984).
d) Ti–Zr–Y discrimination diagram for mafic to intermediate samples (SiO_2 <60%); fields after Pearce and Cann (1973).
e) V–Ti discrimination diagram for mafic to intermediate samples (SiO_2 <60%); fields after Shervais (1982).
Data on diagrams are from present study and Pe-Piper and Wolde (2000).

Great Duck Island, and Flagg Cove formations resemble some components of the New River Terrane (Johnson and McLeod 1996; Johnson 2001). The Cobequid Highlands of northern mainland Nova Scotia (Fig. 1) also contain units similar in rock types and ages to those of Grand Manan Island (Pe-Piper and Wolde 2000; Pe-Piper and Piper 2002). All these areas contain elements of Late Neoproterozoic arcs and associated clastic rocks metamorphosed to greenschist facies.

Future work will entail more detailed comparisons of the stratigraphy, age, and petrochemistry of rocks from the Grand Manan archipelago to better determine the regional significance of pre-Mesozoic geology in the Grand Manan area.

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STRATIGRAPHIC AND STRUCTURAL OBSERVATIONS IN SILURIAN ROCKS BETWEEN POINTE ROCHETTE AND THE SOUTHEAST UPSALQUITCH RIVER, NORTHERN NEW BRUNSWICK: A PROGRESS REPORT

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Rocks of the Silurian Chaleurs Group situated between Pointe Rochette and the Southeast Upsalquitch River provide stratigraphic and structural evidence pertinent to refining the tectonic model for the Late Silurian Salinic disturbance. The Weir Formation records tectonic uplift of the Elmtree Inlier in the late Llandovery, whereas the Simpsons Field Formation reflects uplift of the Miramichi Highlands in the early Ludlow. This tectonic uplift likely was achieved, and/or accompanied, by faulting; however, the faults responsible for uplift can no longer be clearly identified because they have been either buried or overprinted by later fault motions. Fault control of sedimentation can be only inferred from sedimentological evidence such as facies distribution and clast compositions.

Rocks in the study area have been affected by pre-cleavage (F_1) folds, cleavage-related (F_2) folds, and fault-related (F_3) folds. Fault activity is represented by two major sets of faults that overprint the regional folds and Acadian cleavage, one set trending northeasterly and the other trending northwesterly. Stratigraphic and structural data, combined with evidence from elsewhere in northern New Brunswick and the southern Gaspésie, suggest that the Salinic event is related, not to an overall rise in sea level, but instead to diachronous tectonic events that may have begun as early as the late Llandovery.

Des roches du groupe silurien de Chaleurs situé entre la pointe Rochette et le cours inférieur de la rivière Upsalquitch fournissent des indices stratigraphiques et structuraux utiles pour améliorer le modèle tectonique de la perturbation salinique du Silurien tardif. La Formation de Weir témoigne du soulèvement tectonique de l'enclave minière d'Elmtree au cours du Llandovérien tardif, tandis que la Formation de Simpsons Field correspond au soulèvement du massif de Miramichi au cours du Ludlow précoce. Ce soulèvement tectonique a probablement été provoqué par la formation de failles, ou accompagné de failles, mais les failles responsables du soulèvement ne peuvent désormais plus être définies clairement, car elles ont été enfouies ou recouvertes par des mouvements de failles ultérieurs. On peut seulement supposer un contrôle de la sédimentation par des failles d'après certains indices sédimentologiques, comme la distribution des faciès et les compositions de clastes.

Les roches du secteur d'étude ont été affectées par des plis préalables au clivage (F_1), des plis apparentés au clivage (F_2) et des plis apparentés à des failles (F_3). L'activité liée aux failles est représentée par deux ensembles importants de failles qui se superposent aux plis et à la schistosité de l'Acadien : un ensemble en direction nord-est et l'autre en direction nord-ouest. Des données stratigraphiques et structurales, combinées à des indices d'autres endroits de la partie nord du Nouveau-Brunswick et du sud de la Gaspésie, permettent de supposer que la perturbation salinique est apparentée à des phénomènes diachroniques tectoniques distincts qui pourraient avoir débuté dès le Llandovérien tardif plutôt qu'à une élévation générale du niveau de la mer.

INTRODUCTION

The Gaspé Belt in southeastern Québec has been the subject of several recent stratigraphic and structural interpretations (e.g. Dostal et al. 1993; Malo and Kirkwood 1995; Bourque et al. 1995; Bourque et al. 2000). These publications, as well as work conducted elsewhere in the Appalachians of Atlantic Canada (Dunning et al. 1990), suggest that tectonic activity attributed to the Late Silurian Salinic disturbance of Boucot (1962, 1968) persisted from the Wenlock to the Pridoli.

Studies of rocks representing the extension of the Gaspé Belt into northern New Brunswick appear to support this hypothesis (Wilson 2002; Carroll 2003). Nonetheless, several questions remain concerning aspects of the tectonic model.

1) Do early structures in the region represent prolonged and continuous syndepositional deformation, or are they restricted to a particular phase of deformation, presumably the Salinic disturbance?

2) To what extent were the sedimentary sequences in these rocks caused by internal (autocyclic) mechanisms that were controlled largely by sediment supply, as opposed to external (allocyclic) influences such as sea-level change or tectonic uplift?

3) Do the unconformable relationships seen in these rocks reflect a global change in sea level, or do they result from tectonic uplift that accompanied an orogenic event?

Stratigraphic and structural features relevant to these questions can be observed in the rocks of northern New Brunswick near the City of Bathurst. The study area is dominated by sedimentary rocks of the Silurian Chaleurs Group. These rocks underlie an east-northeast-trending depositional basin that extends for 70 km from Pointe Rochette on Chaleur Bay to the Southeast Upsalquitch River area (Fig. 1a, b). The basin is situated between the Elmtree Inlier to the north and the Miramichi Highlands to the south (inset of Fig. 1b), both formed of Ordovician rocks, and is transected by the Rocky Brook–Millstream Fault (RBMF). The Nigadoo River Syncline occurs in the northeastern part of the basin and north of the RBMF (Fig. 1b). Its extension, the Murray Brook Syncline, lies in the southwestern part of the basin and south of the RBMF (Fig. 1a; Skinner 1974).

STRATIGRAPHY SETTING

In the Gaspésie, rocks of the Silurian Chaleurs Group occupy the time span between the Llandovery (Early Silurian) and Pragian (Early Devonian), which corresponds to the interval between the Taconian and Acadian orogenies (Malo and Bourque 1993; Malo and Kirkwood 1995). The rocks show evidence of three shallowing-upward, regressive phases separated by two transgressive phases (Malo and Bourque 1993; Bourque et al. 2000). The second regressive phase (Ludlow–Pridoli) coincides in time with the Salinic unconformity. This disturbance has been noted in uplifted areas throughout the northern Appalachians and, in northern New Brunswick, can be seen at the base of the Indian Point Formation near Campbellton (Wilson 2002).

The Chaleurs Group in the study area is represented by eight formations (Fig. 1, 2). In ascending stratigraphic order, these are the Clemville, Weir, La Vieille, Limestone Point, Simpsons Field, LaPlante, Free Grant, and Budworm City formations (Alcock 1935; Noble 1976; Lee and Noble 1977; Walker and McCutcheon 1995). The four upper formations can be observed throughout the basin (Fig.1), but the Clemville, Weir, La Vieille, and Limestone Point formations are well exposed only along the Chaleur Bay coastline (Fig. 2).

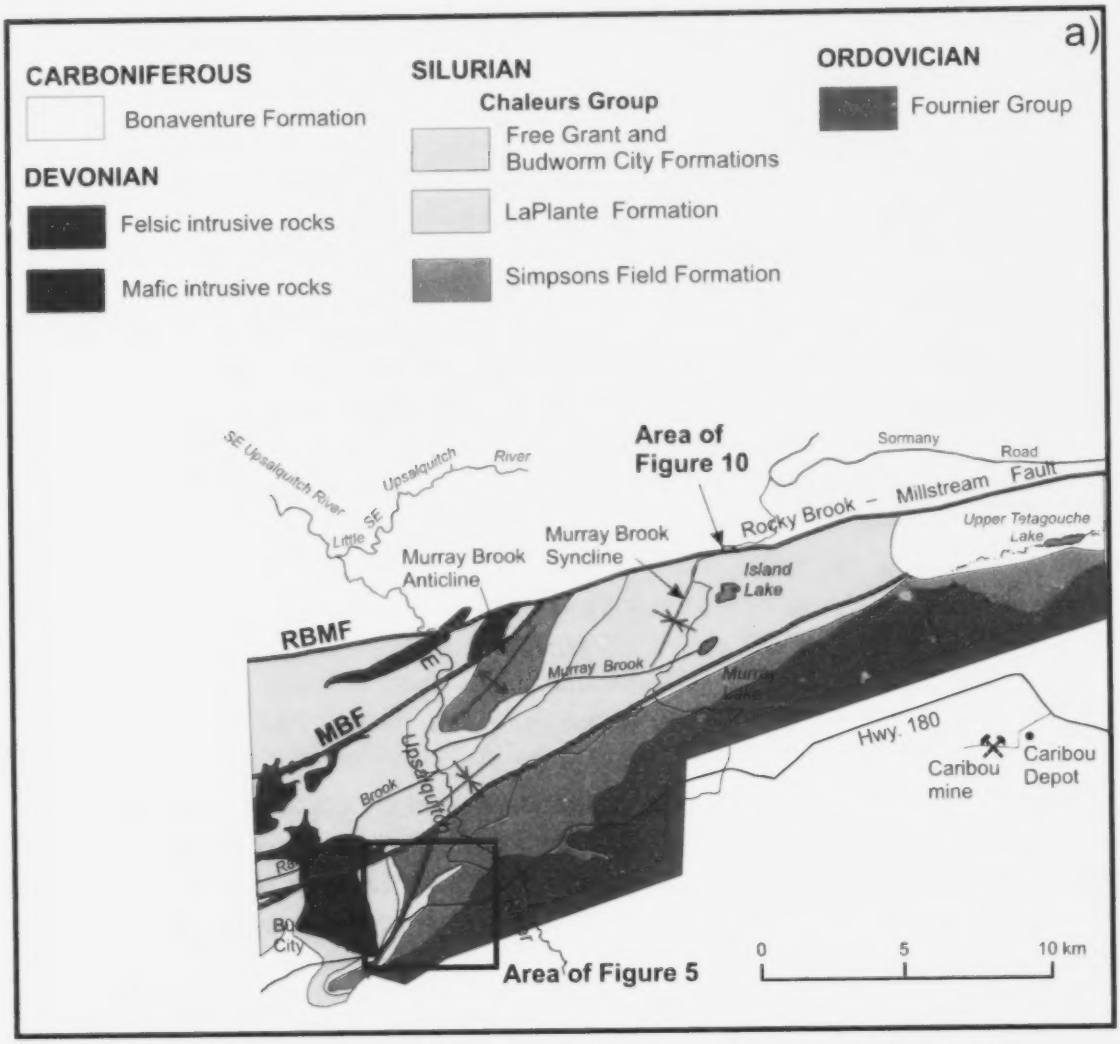


Figure 1a. Simplified geology map of the study area, showing southwestern part of the Silurian depositional basin. Modified after van Staal et al. (2003). Map also marks the location of Figures 5 and 10.

Clemville Formation

Rocks assigned to the Clemville Formation by Walker and McCutcheon (1995) are restricted to the easternmost part of the study area. They comprise grey and green, thick-bedded, tightly folded calcareous siltstone and buff, thin-bedded, ripple-laminated, calcareous sandstone. These lithologies closely resemble upper strata of the type area for the formation in the Gaspésie (Schuchert and Dart 1926).

Siliciclastic limestone beds of the Clemville Formation occur near the mouth of Madisco Brook, where they are up to 1 m thick (Fig. 2). Although the base of the formation is not exposed

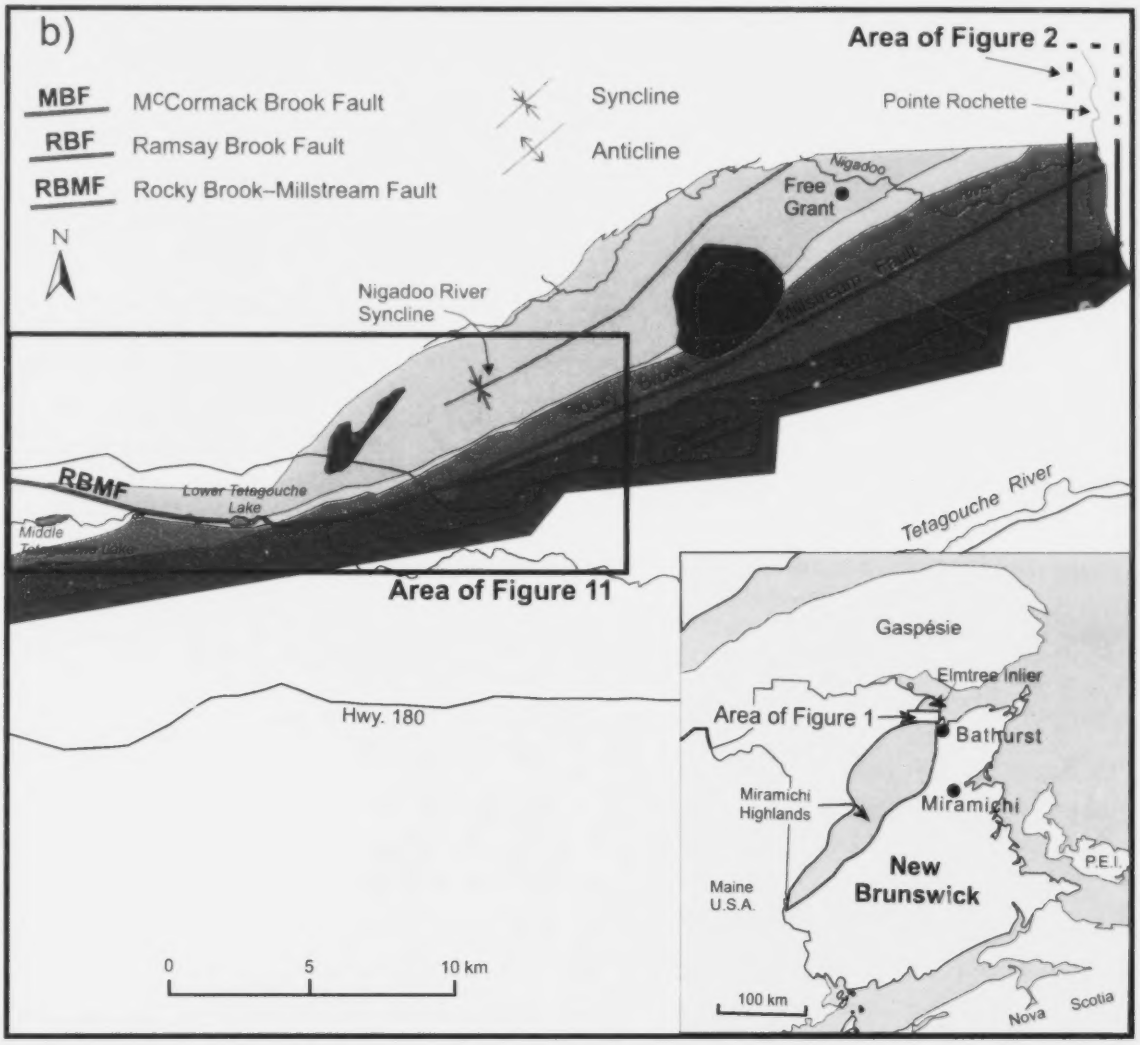
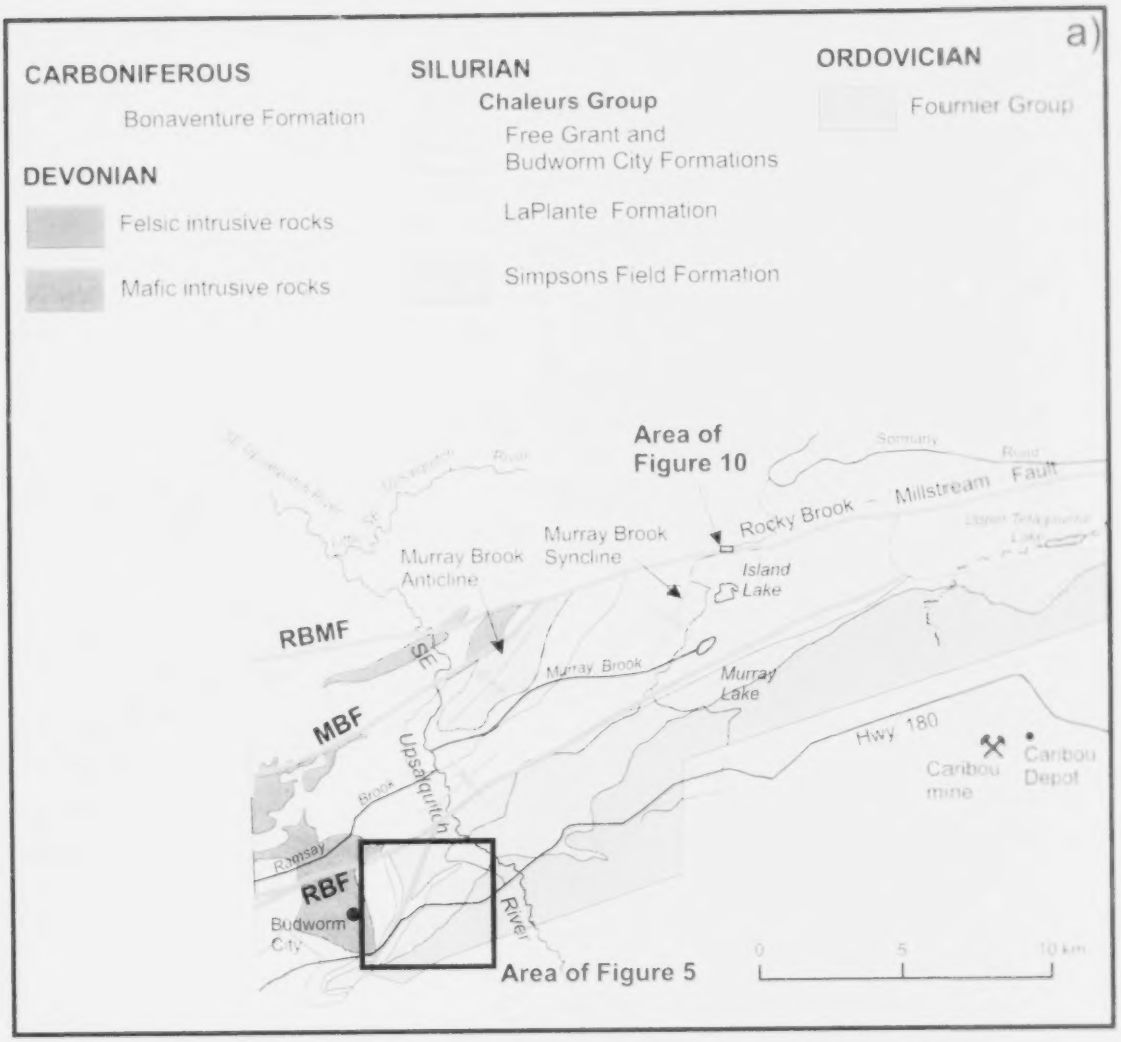


Figure 1b. Same as Figure 1a, but showing northeastern part of the Silurian depositional basin. Map also marks the location of Figures 2 and 11.

in the study area, calcareous shale assigned to the unit appears in gradational contact with underlying 'ribbon limestone' of the Matapedia Group at Black Point and Nash Creek farther northwest (Irrinki 1990).

Noble (1976) inferred a turbiditic origin for the finer grained calcareous rocks, which appear to have formed in a fairly deep-water depositional environment. The Clemville Formation in the Gaspésie has been dated as early Llandoverian on the basis of brachiopods and conodont data (Boucot and Bourque 1981; Nowlan 1983); however, brachiopods from the Clemville Formation at Nash Creek are early to middle Llandoverian (Irrinki 1990).



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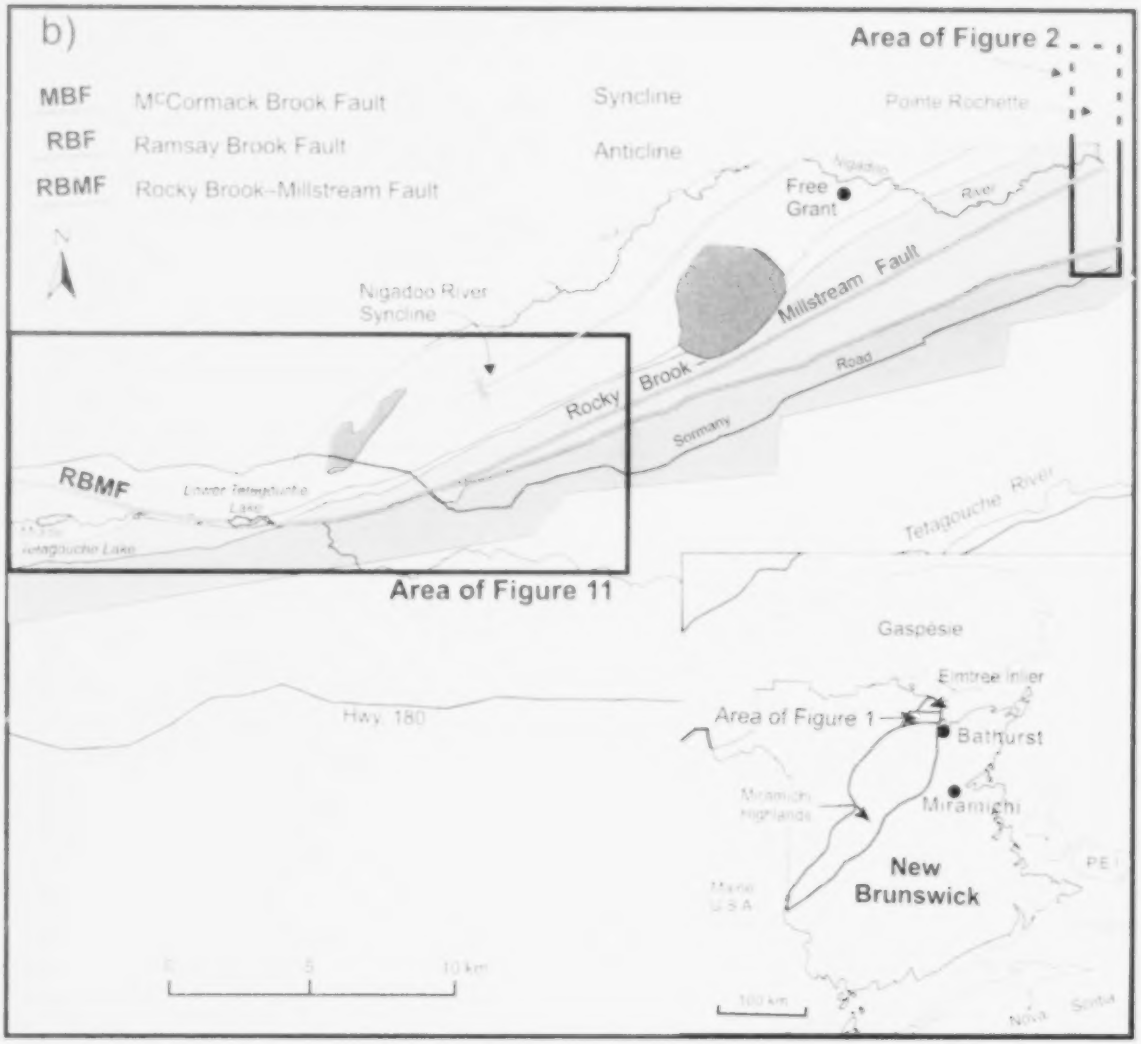

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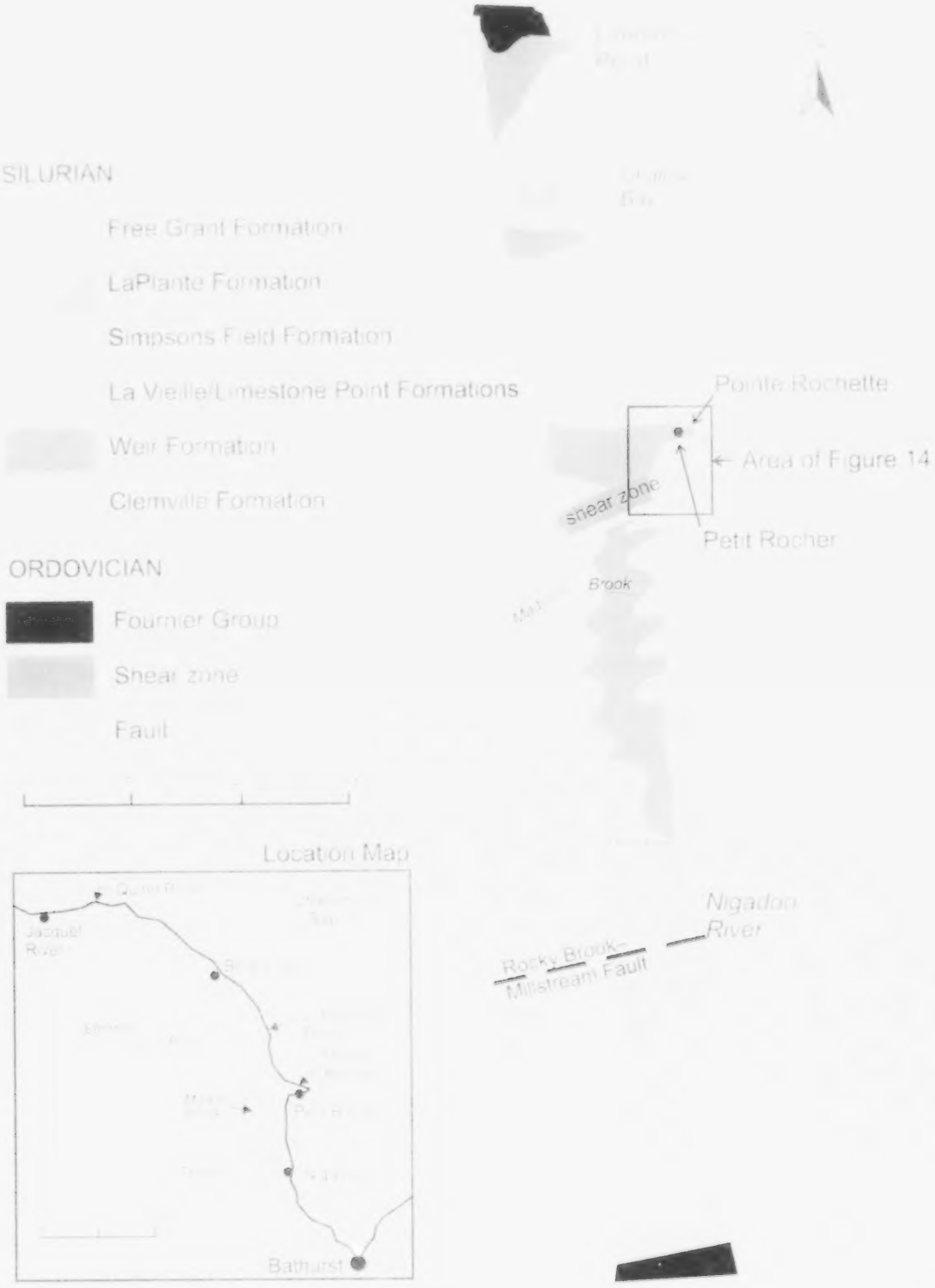


Figure 2 Geology map of the Chaleur Bay coastline between Limestone Point and Nigadoo River. Modified after Walker et al. (1993b). The location of this map is shown on Figure 1b.

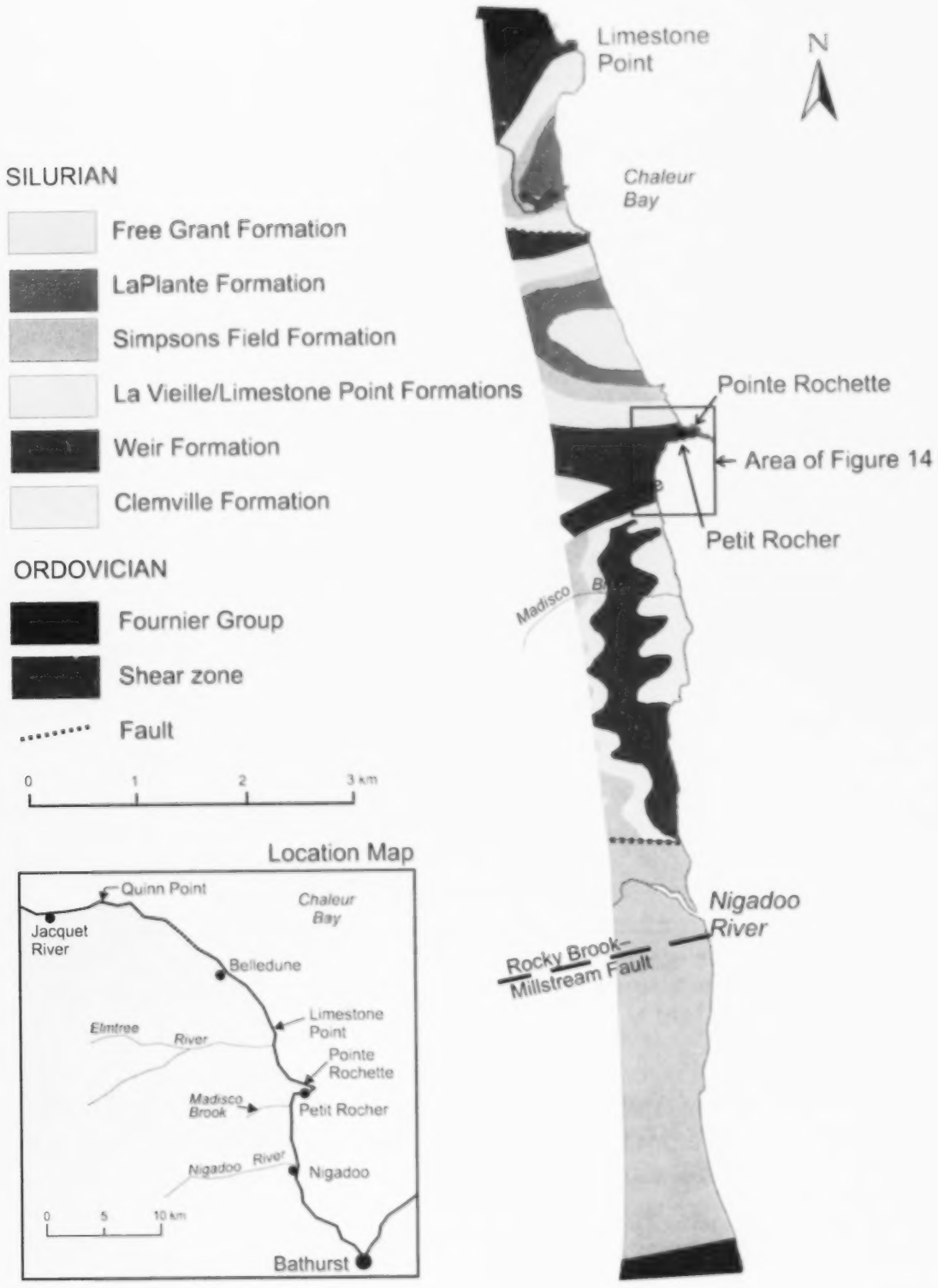


Figure 2. Geology map of the Chaleur Bay coastline between Limestone Point and Nigadoo River. Modified after Walker et al. (1993b). The location of this map is shown on Figure 1b.

Figure 3. Contact between pebbly sandstone of the Weir Formation and dark limestone of the La Vieille Formation. The uneven contact (shown as red line) is marked by pebbles protruding into the limy rocks, and is due to differential loading. The compass is 16 cm long.

Weir Formation

The Weir Formation is found only in proximity to the Elmtree Inlier, where it unconformably overlies Ordovician rocks of the Fournier Group (inset of Fig. 1b, Fig. 2; Lee and Noble 1977; Fyffe and Noble 1985).

Rocks of this formation consist largely of red and green grit, sandstone, and conglomerate, and appear to have formed in a fluvial to near-shore environment (Noble 1976). Pebbles in the conglomerate are predominantly volcanic rock but include clasts of quartz, jasper, chert, and sedimentary rock (Fig. 3). The composition of clasts in the conglomerate indicates they were derived from the nearby Ordovician rocks. Conodonts from a basal calcareous sandstone on Limestone Point and brachiopods higher in the section date the Weir Formation as late Llandoverian (Nowlan 1988b; Noble 1976).

Farther into the Silurian basin, near Pointe Rochette, the Weir Formation is interpreted to disconformably overlie calcareous turbidites assigned to the Clemville Formation (Walker and McCutcheon 1995). Alcock (1935), however, suggested significant fault displacement along that contact to explain the juxtaposition of coarse-grained, subaerial to shallow-marine red clastics of the Weir Formation, and fine-grained, deeper water sediments of the Clemville Formation (*see* ***Shear Zones of Uncertain Tectonic Origin*** below).

Figure 4. Nodular black limestone of the La Vieille Formation. The hammer handle is 45 cm long.

Limestone Point Formation

The Limestone Point Formation consists of greyish-green, bioturbated, parallel-laminated (or, more rarely, cross-laminated), medium-grained, calcareous sandstone interbedded with lenses of limestone. Brachiopods and conodonts within the formation are interpreted as being late Llandoverian to early Wenlockian (Noble 1976; Nowlan 1983). The concordant boundary between the calcareous sequence of the Limestone Point Formation and the underlying conglomeratic sequence of the Weir Formation is fairly sharp (Noble 1976; Lee and Noble 1977).

In the study area, the Limestone Point Formation occurs only around Limestone Point (Fig. 2). Farther south, this sandy calcareous facies interfingers with, and ultimately is replaced by, the carbonate facies of the La Vieille Formation, leaving the latter formation in direct contact with the Weir Formation (Fig. 3).

La Vieille Formation

The La Vieille Formation consists of nodular, black limestone and thin- to medium- bedded, highly fossiliferous, dark grey limestone interbedded with minor light grey calcarenite, and fine-grained, greenish-grey sandstone (Fig. 4). The sequence is interpreted to have formed in a shallow-water marine environment (Howells 1975; Noble 1976; Lee and Noble 1977; Nowlan 1983). Brachiopods and conodonts within the formation indicate an age of late Llandovery to Wenlock.

Simpsons Field Formation

Rocks of the Simpsons Field Formation typically include greenish-grey and locally red pebble to cobble conglomerate, sandstone, and siltstone. The conglomerate contains clasts of chert, quartz, jasper, red and green siltstone, mafic and felsic volcanic rocks, slate, gabbro, limestone, granitoids, and feldspar porphyry. Many of the clasts show lithological similarities to, and clearly were derived from, proximal Ordovician rocks of the Miramichi Highlands. Brachiopods found in sandy beds intercalated with the conglomerate indicate that the age of the formation is Ludlow (Potter 1965; Helmstaedt 1971).

In the southwestern part of the Silurian basin, the Simpsons Field Formation flanks, and unconformably overlies, the Ordovician Fournier Group of the Highlands to the south (Fig. 1a). It consists mainly of a coarse facies comprising a pebbly, matrix-supported conglomerate, in which the matrix is composed predominantly of iron-stained, immature dark sand. The clasts are moderately rounded with a chaotic imbrication pattern and long-axis orientation. This pebbly facies occurs in lenses of irregular lateral extent and thickness, interbedded with dark green or greenish-grey, immature sandstone containing dispersed pebbles. Sharp bedding surfaces are rare, but diffuse transitional zones between lenses are common. Grading of beds is chaotic and shows no observable cross-stratification in the pebble conglomerate and grit. Local, small channels are up to 2 m deep, filled with large clasts and fossil debris.

In the Sormany quarry area — that is, in the northeastern part of the basin and north of the RBMF (Fig. 1b) — a facies of pebbly, matrix-supported conglomerate and sandstone is interbedded in cycles of thickening-coarsening and thinning-fining. Each depositional cycle has an average thickness of 5 to 10 m. These rocks indicate proximity to the basin margin, even though they lie north of the RBMF. Along strike, approximately 10 km to the northeast, similar conglomerate forms the upper part of a coarsening-upward sequence that conformably overlies the La Vieille Formation (Walker and McCutcheon 1995). About 25 km northeast, a finer grained, distal facies of the Simpsons Field Formation is exposed at the Nigadoo River. Rocks alongside the river show abundant sedimentary structures and incomplete Bouma sequences, which suggest a turbidite origin.

Yet in the northeastern part of the basin to the south of the RBMF, conglomerate is absent from the section. At the unconformable contact between Ordovician rocks of the Miramichi Highlands, calcareous strata are present that probably are equivalent in time to the La Vieille Formation. This contact has been interpreted as a faulted unconformity and on Figure 1b appears as an unnamed splay of the RBMF (see ***Northeasterly Trending Faults*** below). Conodonts from these calcareous rocks are Silurian, possibly early to middle Llandoverian (McCracken 1989, written communication), which suggests that the rocks probably are time equivalent to limestone

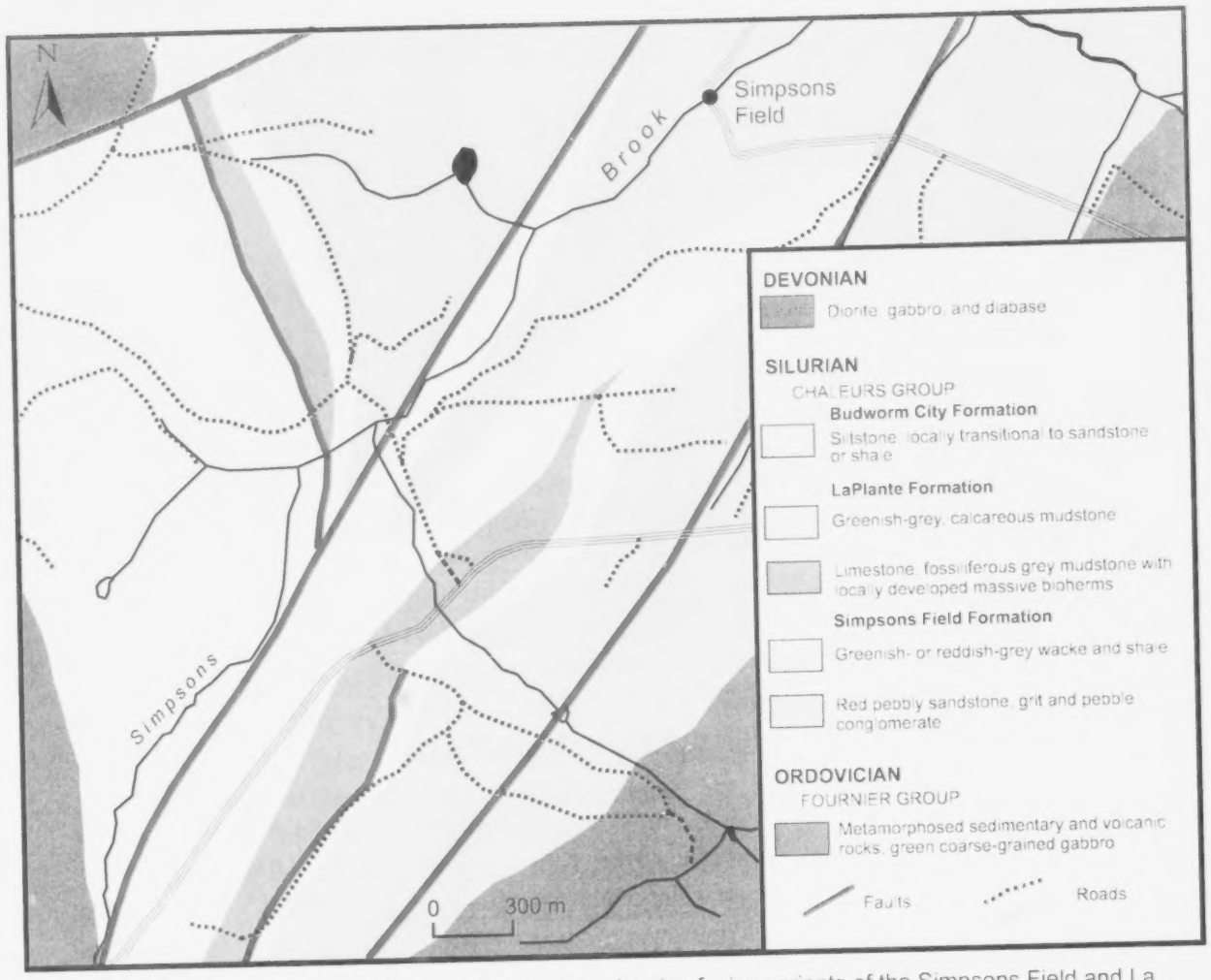
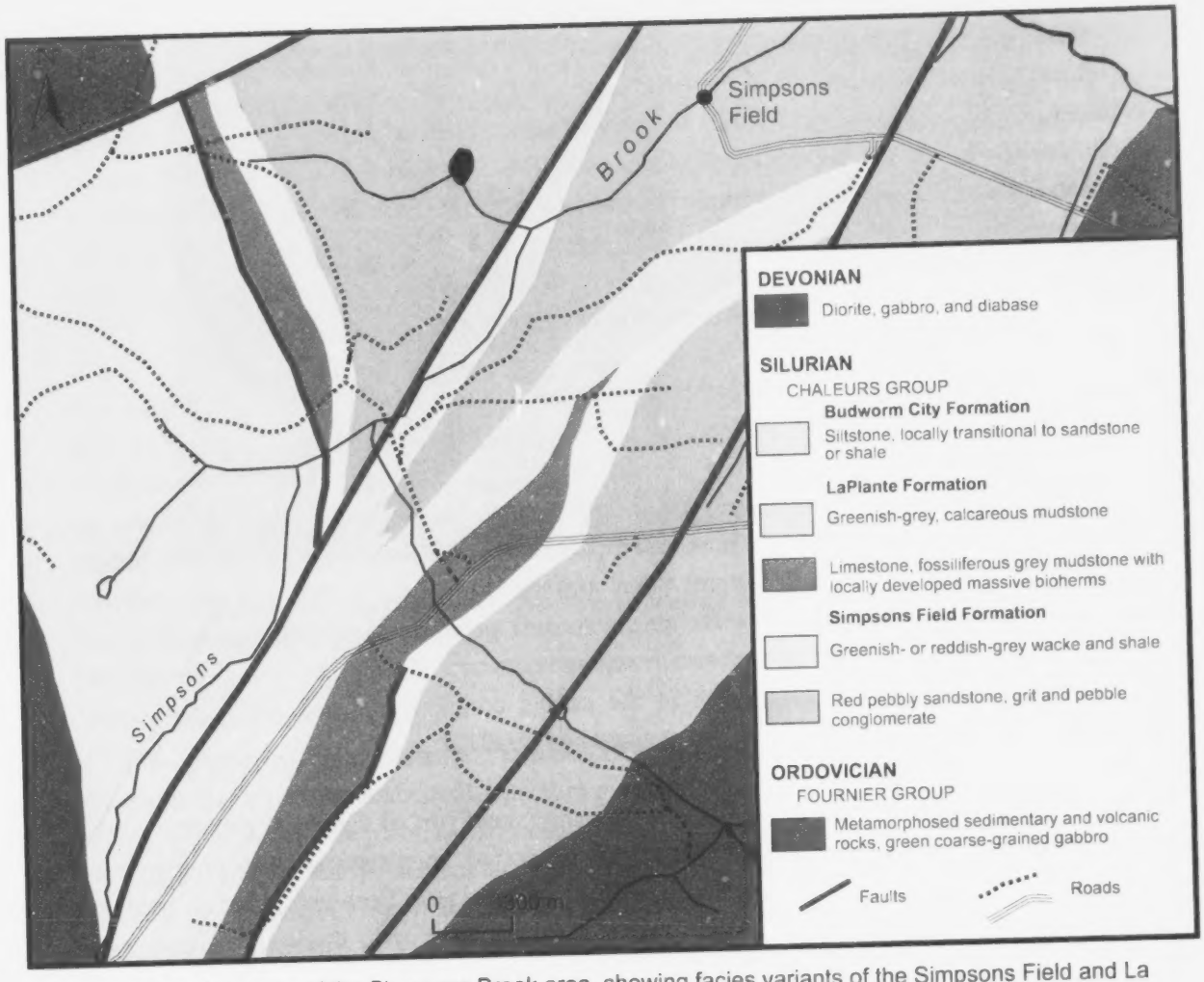


Figure 5. Geology map of the Simpsons Brook area, showing facies variants of the Simpsons Field and La Plante formations. The location of this map is marked on Figure 1a.

of the La Vieille Formation. Overall, the clastic sequence above the calcareous rocks fines upward, in contrast with the post-La Vieille sequence immediately north of the RBMF, which coarsens upward. Movement along the RBMF therefore appears to have significantly influenced the deposition of coarse facies within the Simpson Field Formation.

On the Chaleur Bay coast, immediately south of Limestone Point, an angular unconformity separates the Simpsons Field Formation from underlying nodular limestone of the La Vieille Formation (Fig. 2). Above the unconformity is a discontinuous lens of polymictic boulder conglomerate that averages about 1 m in thickness. Most of the boulders consist of black massive limestone, but locally the siliciclastic matrix encloses fragments of orange chert and dark grey shale. This conglomerate is overlain by greenish-grey, thin- to medium-bedded, calcareous sandstone containing limestone lenses, which passes upward into mudstone.



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LaPlante Formation

The LaPlante Formation has been traced across the study area, almost without interruption, for the full length of the contact between Ordovician and Silurian rocks along the northern margin of the Miramichi Highlands in the southwestern part of the basin (Fig. 1a), and north of the RBMF in the northeastern part of the basin (Fig. 1b). The formation includes elongated, laminated, fringing reefal limestone and calcarenite; grey and buff, massive to nodular limestone; thin-bedded, black to grey micritic limestone interbedded with dark grey, fossiliferous siltstone and calcareous shale; and minor red conglomerate and siltstone (Noble 1985). Its age is Pridoli, as evidenced by conodonts found in the formation (Nowlan 1982, 1983, 1988b).

Locally, either limestone or calcareous shale predominate. The thicker limestone units are interpreted as small, stromatoporoidal-stromatolitic reefs, whereas the more clastic rocks represent inter-reef deposits (Noble 1985; Fyffe and Noble 1985). Evidence suggests that some reefal mounds are allochthonous, as they are underlain by mudstone showing soft-sediment deformation. Reefs in the vicinity of the RBMF have been thickened by tight folding (Dimitrov et al. 2003).

A thin, transitional zone of fossiliferous, calcareous mudstone occurs between the LaPlante Formation and the conformably underlying Simpsons Field Formation (Fig. 5). The zone contains dispersed laminar spheroids of algal origin that measure up to 15 cm in diameter, and solitary rugose corals. The quantity of fossil debris increases upsection. Above the mudstone are thin (3–5 cm) beds of white calcarenite rhythmically interlayered with grey to greenish-grey siltstone. The calcarenite beds comprise sand-size fragments of corals, brachiopods, echinoderms, and other fossils.

Calcareous reefs in this formation show no evidence of lateral progradation or polycyclic growth (Noble 1985). Their simple architecture indicates gradational growth during a single transgressive event or period of tectonic stability. The reefs are overlain by shallow-water siliciclastics, which strongly suggests that they were suffocated during excessive influx of terrigenous material. Suffocation of reefs by siliciclastic sedimentation also has been suggested for the reefal complex of the West Point Formation in the Port Daniel area of the Gaspésie (Bourque et al. 1986).

Free Grant Formation

The Free Grant Formation is the youngest unit of the Chaleurs Group exposed in the Nigadoo River Syncline area. Its rocks comprise thin-bedded, ripple-laminated, weakly calcareous sandstone alternating with medium-bedded, greenish-grey siltstone, and minor green and red shale (Walker and McCutcheon 1995).

The Free Grant Formation conformably overlies the LaPlante Formation or, where those rocks are absent, the Simpsons Field Formation. It contains abundant sedimentary structures such as load casts, graded bedding, and cross bedding, distinguishing it from the LaPlante and Simpsons Field formations. The Free Grant Formation of the Nigadoo River Syncline apparently is laterally equivalent to the Late Silurian Budworm City Formation, which overlies the LaPlante Formation in the Southeast Upsalquitch River area of the Murray Brook Syncline (Fig. 1a).

Budworm City Formation

The Budworm City Formation comprises grey to greenish-grey or black siltstone, fine- to medium-grained sandstone, and minor limestone and conglomerate. It conformably overlies the LaPlante Formation and is considered coeval with the Free Grant Formation, which overlies the LaPlante Formation in the Nigadoo River Syncline on the northern side of the RBMF. Southwest of the study area, the Budworm City Formation is conformably overlain by, and, in part, interfingers with, redbeds of the Greys Gulch Formation (Walker and McCutcheon 1995).

Late Silurian conodonts in the underlying LaPlante Formation (Nowlan 1983) indicate that the age of the Budworm City Formation is no older than Pridoli. The Mulligan Gulch Porphyry, which intrudes rocks of the Budworm City Formation, has been radiometrically dated (U–Pb zircon) at 419 ± 1 Ma (McCutcheon and Bevier 1990).

STRUCTURAL SETTING

The northeastern and southwestern parts of the study area span two distinct structural domains separated by the RBMF (Fig. 1). The northeastern domain lies north of the fault, in the area referred to as the Nigadoo River Syncline, and stretches eastwards to the Chaleur Bay coastline. The southwestern domain lies south of the RBMF, encompassing the Murray Brook Syncline, and reaches westwards to and beyond the Southeast Upsalquitch River. The two structural domains exhibit differences in regional trends of major folds, cleavage orientation, and fold-cleavage relationships.

Rocks in the northeastern domain display two phases of folding. First-phase folds (F_1) occur in rocks older than the Simpsons Field Formation and predate the regional cleavage (Fig. 6, 7). Large, second-phase folds (F_2) affect rocks of the Simpsons Field Formation and other, younger Silurian formations as well as Lower Devonian rocks. The F_2 folds trend 40° to 70° with a mean orientation of 60°. First-phase folds are absent from the southwestern domain, which includes no units older than the Simpsons Field Formation. On the other hand, rocks in this domain are affected by F_2 folds that trend around 30°, and by later folds (F_3) that apparently are restricted to lithologies near the RBMF. It is noteworthy that two phases of folding also have been recognized in Silurian rocks of the Gaspé Belt (Malo and Beland 1989; Malo and Kirkwood 1995).

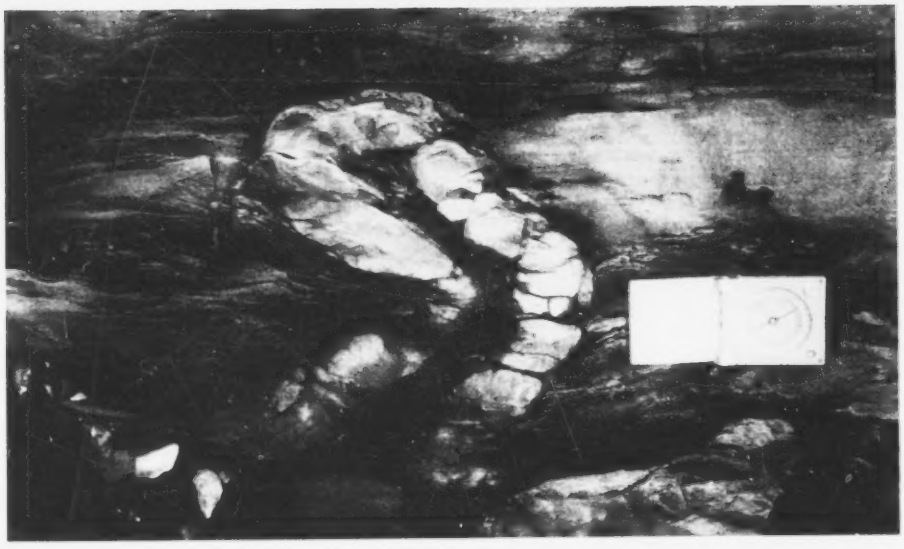

Figure 6a. Rootless F_1 folds in rocks exposed near the Petit Rocher lighthouse, where regional cleavage overprints both fold limbs at a high angle. The compass is 16 cm long.

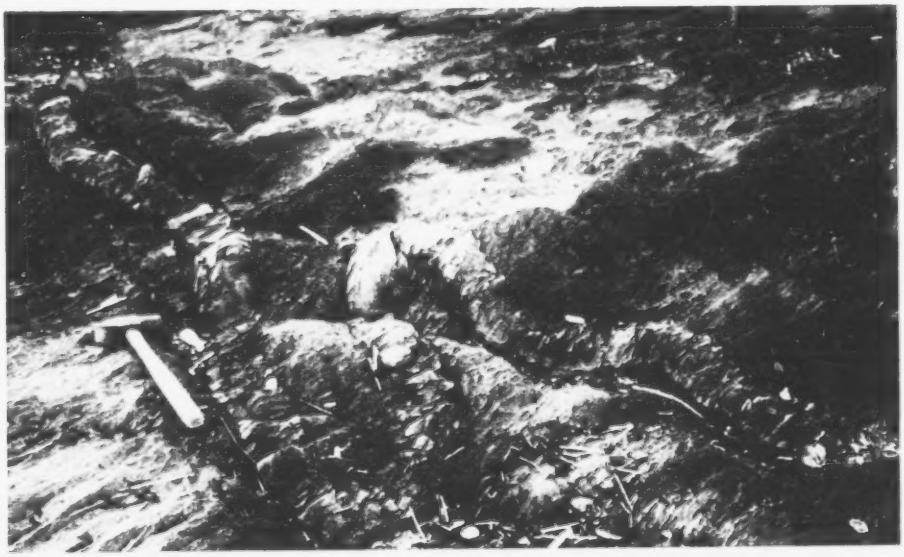

Figure 6b. F_1 folds from the same location as Figure 6a. The hammer handle is 45 cm long.

The earliest folds trend northwesterly and lack a penetrative cleavage. The later folds trend northeasterly and are associated with a regionally developed cleavage that transects some folds (Malo and Beland 1989; Malo and Kirkwood 1995; Bourque et al. 2000). Regional cleavage typically strikes 30° to 45° and dips 60° to 90° in the northeastern domain; it strikes 15° to 30°

and dips 40° to 80° in the southwestern domain. In both areas, cleavage is well developed in muddy rock types but practically absent in sandy lithologies. Cleavage refraction can reach 35° to 40° and occurs, not only between individual beds, but also between rock sections, which are 20 to 50 m thick. Where competent and incompetent beds are equally represented in the sedimentary sequence, cleavage orientation is relatively consistent.

Fold-cleavage relationships also differ between the two domains. Regional cleavage in the northeastern area transects the first-phase folds, many second-phase folds, and the Nigadoo River Syncline itself. Along the coast, significant non-coplanarity exists between the regional cleavage and the orientation of axial planes of folds (Stringer 1975). By contrast, cleavage in the southwestern domain is roughly axial planar to the large, F_2 folds.

Folds: in Detail

The three generations of folds are distinguished on the basis of their shape, orientation, size, associated small structures, and relationship to the regional cleavage.

Pre-cleavage (F_1) Folds

In the northeastern domain, pre-cleavage folds have been observed only in rocks older than the Simpsons Field Formation — that is, they are pre-Ludlovian. Fold size varies from several centimetres to several metres. The folds are tight and have curved axial planes with amplitudes most commonly in the range of 1 to 2 m (Fig. 6a, b). They show no axial plane cleavage but are cut at a high angle by the regional cleavage. Younging of the strata is locally downward, and undeformed fragile fossils are preserved in the folds. Some of the folds occur in distinct stratigraphic horizons with undisturbed beds above and below the horizon. These folds are asymmetrical and have consistent vergence.

At Limestone Point, many F_1 folds plunge northwest or southeast (Fig. 7a, b), contrasting with the typical northeast- or southwest-plunging regional trends of the later Silurian folds. Recumbent F_1 folds are common in this location. Pre-cleavage, F_1 folding also occurs near the Petit Rocher lighthouse, where a 6 m thick disturbed section includes dismembered, folded strata (Fig. 6a, b; Fig. 8). The fold has a depositional contact at the top but is detached at its base. Strata young in the same direction below and above the disturbed section. Despite the intensity of folding, there is no axial-plane cleavage or evidence of syndeformational veining such as saddle reefs. The disturbed section occupies the southern limb of a large F_2 anticline and plunges southwest (Fig. 9).

The preceding observations suggest that the F_1 folds predate regional folding associated with the Acadian Orogeny, which van Staal and de Roo (1995) interpreted as a transpressive event; however, the precise timing of F_1-fold formation is unclear. It also is uncertain whether the F_1

Figure 7a. Shear surfaces (shown as red lines) displace small F_1 folds (outlined by black lines) at Limestone Point. The blue GPS unit is 10 cm long.

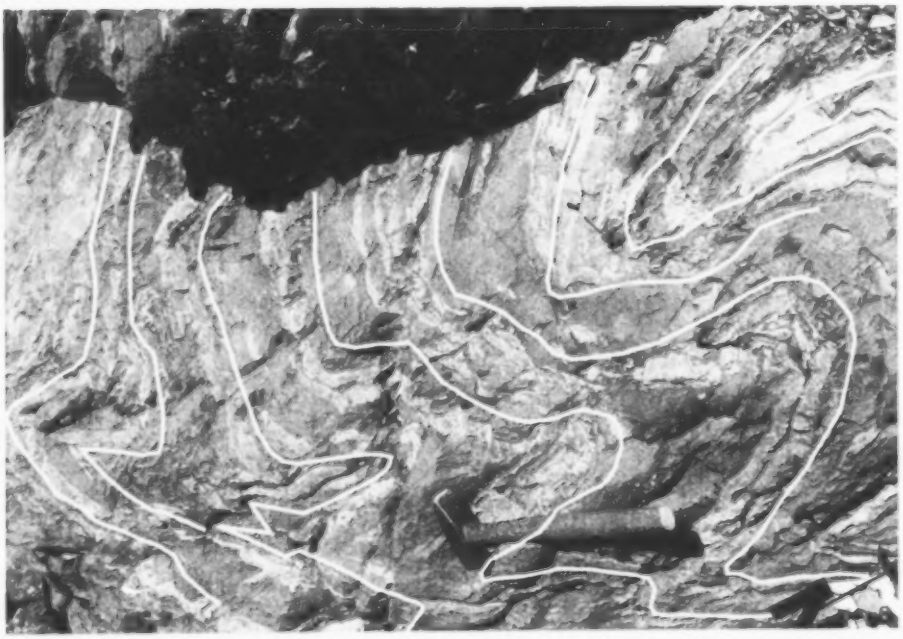

Figure 7b. Bedding (outlined by yellow lines) contorted by F_1 folds in rocks at Limestone Point. The hammer handle is 45 cm long.

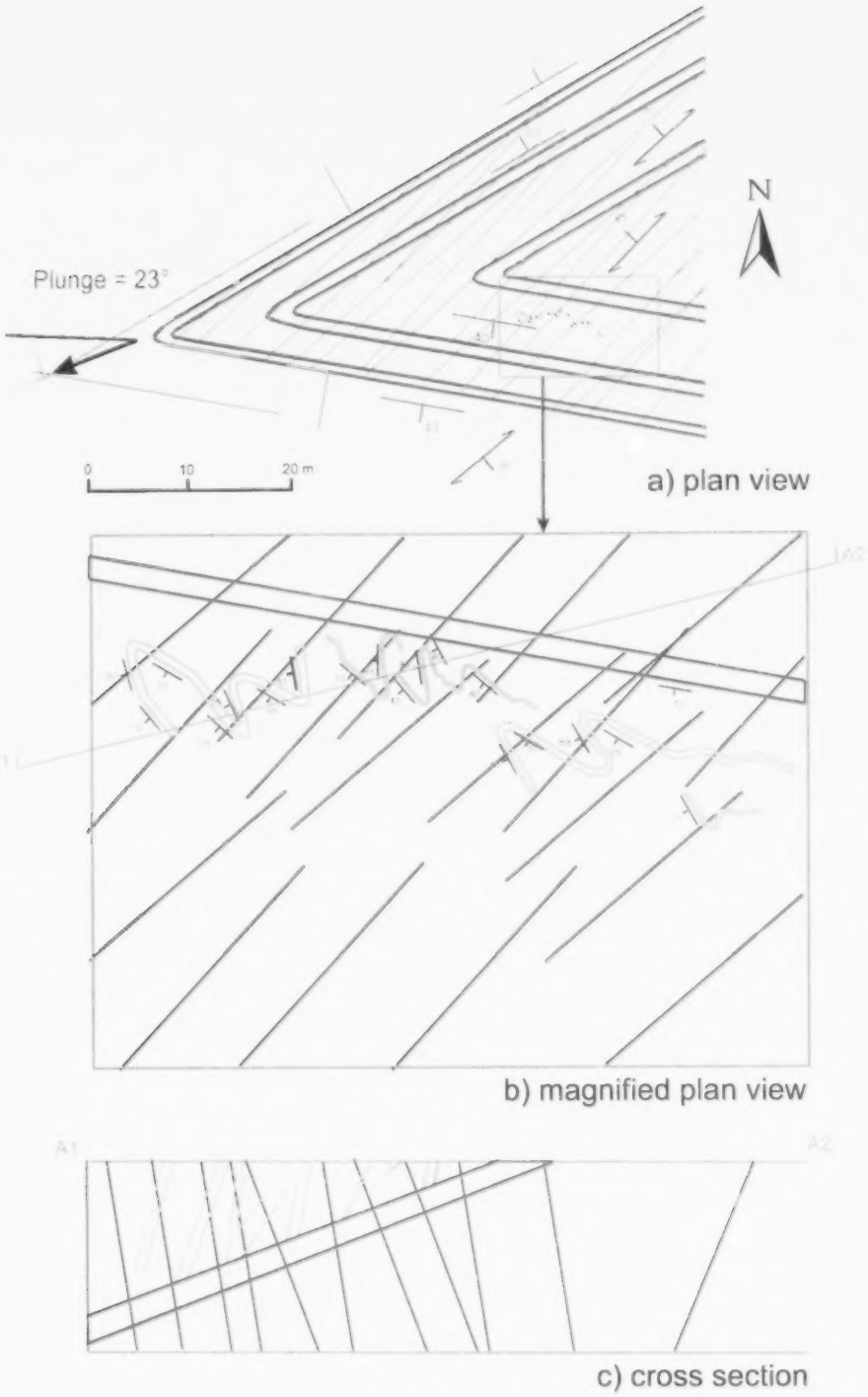

Figure 8. Detailed structural map of coastal rocks near Petit Rocher lighthouse, where regional, northeast-trending cleavage transects F_1 and F_2 folds. The small folds in Figure 6 also are from this location. a) Plan view of large F_2 fold containing F_1 folds on its southern limb. Shows structural contours and plunge of F_2. b) Magnified plan view of Figure 8a. c) Cross section of Figure 8b.

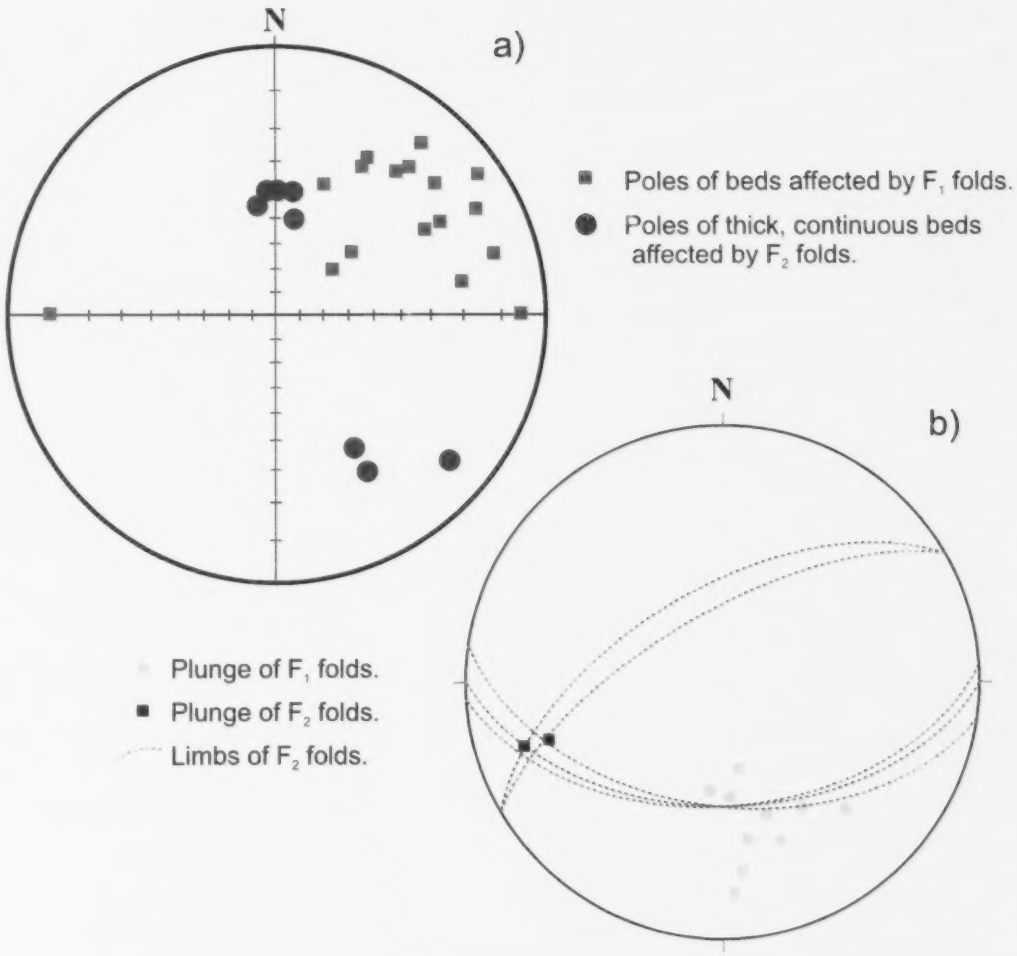

Figure 9. Equal-area, lower hemisphere projections of rocks in Figure 8, showing a) poles of the beds, and b) axes of the folds.

folds were produced by near-surface, soft-sediment deformation or by more significant, regional subsurface tectonic processes. Some F_1 folds may have formed at the time of deposition, whereas others may have been created after deposition but before Acadian deformation.

Cleavage-related (F_2) Folds

Rocks in both domains have been folded into large, upright, open to tight folds (F_2) that plunge shallowly to the northeast or southwest, except where F_1 folds are present. The intensity of associated small-scale folding appears to have varied considerably. The thin-bedded rocks of the Clemville and La Vieille formations in the northeast consist primarily of calcareous siltstones and calcilutite interbedded with mudstone; these rocks contain abundant small folds. By contrast, the more competent rocks of the Simpsons Field Formation have fewer small-scale folds on the limbs of larger folds, and the bedding dips consistently in one direction for hundreds of metres.

In the northeastern area (Fig. 2), wavelengths of the F_2 folds vary from tens of metres to hundreds of metres, and parasitic folds occur on limbs of the largest folds. The F_2 folds are cut by a regionally developed cleavage that trends northeasterly. The cleavage refracts and fans as it passes through different layers. For some folds, the cleavage is transecting (Fig. 8a–c), whereas for others it is more or less axial planar. Cleavage commonly strikes more northerly than do axial planes of the folds. Veins parallel to the bedding are common and are interpreted as being coeval with the F_2 folds. Differential displacement along the cleavage has locally folded calcite-filled veins and disrupted nodular limestone beds. In places, the bedding is offset along calcite veins by more than 1 m of apparent displacement.

Fault-related (F_3) Folds

All F_3 folds postdate the regional cleavage and appear to be confined to faults near or within the RBMF zone. Two sites with good exposure of these fault-related folds — the Sormany quarry, and just north of Island Lake — are discussed below under ***Northeasterly Trending Faults.***

Faults: in Detail

The study area contains many sizeable faults of varying age and structural significance, which can be grouped into two main categories. Faults in the first group trend northeasterly, and those in the second group trend northwesterly. These faults correlate to the 'longitudinal' and 'transverse' structures respectively of Davies et al. (1969). The northeasterly trending Rocky Brook–Millstream Fault is the longest and most important fault in the study area (Fig. 1a, b). Also present are numerous smaller faults and shear zones of variable orientation.

Northeasterly Trending Faults

Northeasterly trending faults occur in the northeastern (Davies et al. 1969; Walker et al. 1993a–c) and southwestern (Helmstaedt 1971; Walker and McCutcheon 1990; Bourque et al. 1995; Wilson 2003) domains of the study area. The most significant of these is the RBMF, which transects the entire district (Fig. 1a, b).

In the northeastern domain, other substantial faults occur, including one positioned along the unconformable contact between Ordovician rocks of the Miramichi Highlands and Silurian rocks (Fig. 1b). This structure formerly was called the Rocky Brook Fault by Davies et al. (1969), who described it as a splay of what they termed the 'Main Break'. The Main Break subsequently became known as the Rocky Brook–Millstream Fault.

In the southwestern domain, the only named northeasterly trending faults are the Ramsay Brook Fault (RBF) and the McCormack Brook Fault (MBF), which also are considered to be splays of the RBMF (Fig. 1a).

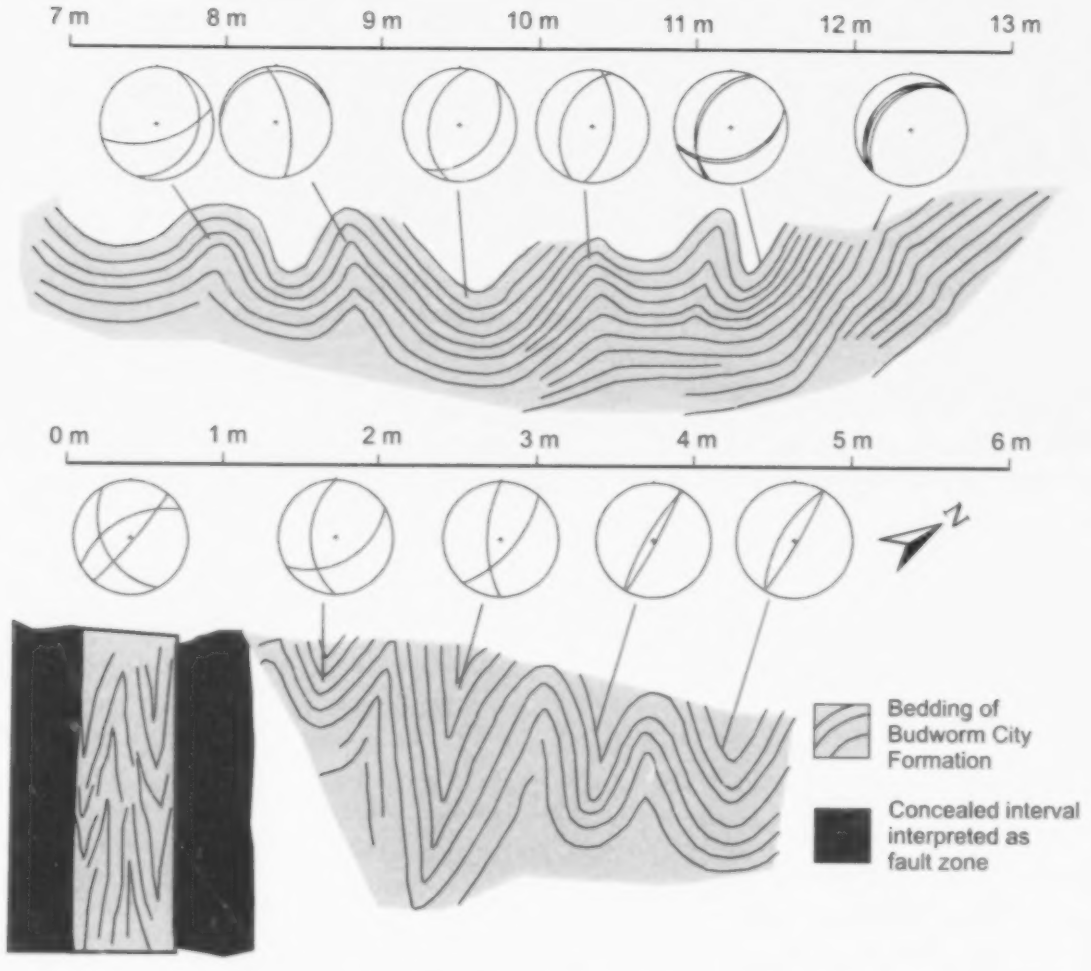

Figure 10. Field drawing of folds in thin-bedded, silty dolomites of the Budworm City Formation, near the Rocky Brook–Millstream Fault. The rocks are not significantly affected by regional cleavage. The intensity of folding increases gradually toward the fault zone. Scale in metres represents the distance away from the high-strain zone of the fault. The location of this figure is shown on Figure 1a.

The RBMF changes direction along strike in the study area. East of Lower Tetagouche Lake it strikes at approximately 250°, between Lower and Upper Tetagouche lakes it strikes at 285°, and farther west it strikes at about 260°. Poor exposure restricts detailed structural analysis of the RBMF to only a few locations throughout the district — none of them east of the Sormany quarry. Sites with good fault exposure occur near Island Lake, which lies immediately south of the fault in the southwestern domain (Fig. 1a); and in the Sormany quarry, which is adjacent to the fault zone and east of Lower Tetagouche Lake (Fig. 1b).

Just north of Island Lake, a roadcut crossing the RBMF exposes rocks of the Budworm City Formation (Fig. 1a). The strata show evidence of fault-related, F_1 folding. Observed deformation in the rocks intensifies over a distance of 13 m, changing gradually from gently folded strata to tightly folded, sheared, and transposed strata as the fault zone is approached (Fig. 10). Small folds in the

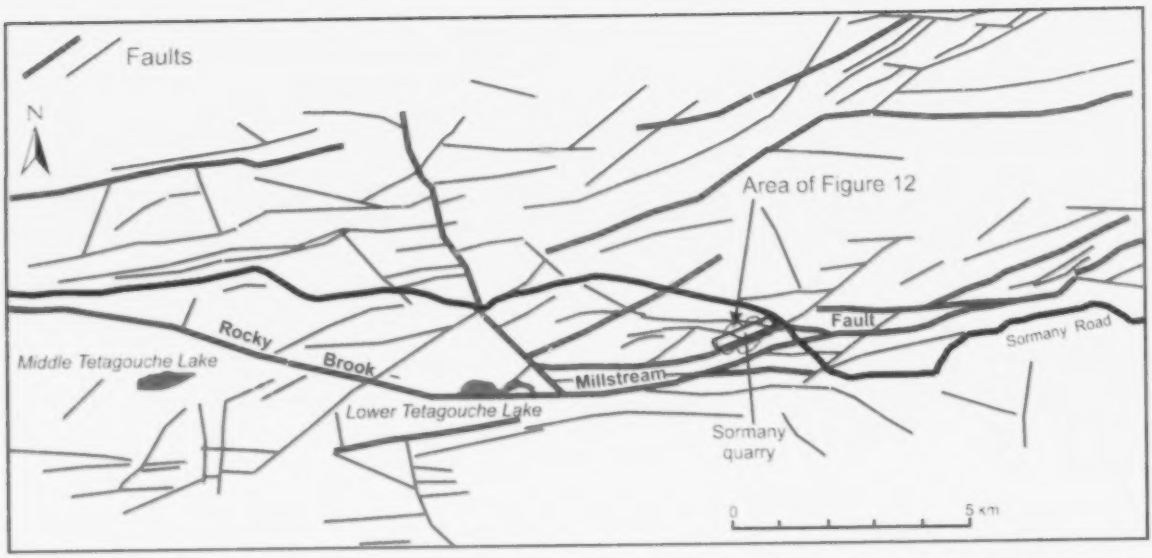

Figure 11. Presumed fault lineaments around the Tetagouche lakes, as detected on Landsat images and aerial photographs. Thicker lines designate the more significant structures. The black arrow indicates the site of a high-strain zone in the Sormany quarry, as illustrated in Figure 12. The location of Figure 11 is shown on Figure 1b.

rocks are superimposed on strata that previously were deformed by large, gentle F_2 folds. The axial planes of these small folds lie oblique to the fault and grow progressively tighter until becoming isoclinal toward the high-strain zone of the fault. Shearing and transposition of the beds has produced near-vertical dips and in places has totally obliterated the folds. Cleavage coeval with the folding has not developed here, likely because the rock is a competent silty dolomite, not a clay-rich rock containing minerals that could alter readily to phyllosilicates.

Folding in the exposure near Island Lake is interpreted as being fault-related for the following reasons: 1) the F_3 folds contrast markedly in size and geometry with the regional, large-scale folds, 2) the interior of the fault zone exhibits a strong deformational gradient, and 3) axial planes of the folds trend northerly and are oblique to the fault zone, a relationship that resembles models for the formation of oblique folds in strike-slip fault zones (*see* Sylvester and Smith 1988). Significantly, folding of this nature (F_3) in the study area is documented only in the vicinity of the RBMF zone.

Fault-related, F_3 folding also can be seen in the Sormany quarry (Fig. 11), where oblique folds occur on the scale of hundreds of metres (Dimitrov et al. 2003). These tight, doubly plunging folds have axial planes that strike more northerly than the fault zone. Cleavage in the clay-rich, calcareous siltstones is parallel to the fold axial planes but oblique to the fault zone. Thrusts, shallowly dipping strike-slip faults, and intense subhorizontal fractures are common here and are interpreted to reflect vertical extension (Dimitrov et al. 2003). Decimetre-scale, steeply plunging folds are oblique to the shear-zone boundaries. As well, small drag folds and sheath folds with horizontal axes occur in the deformation zone of the RBMF at this site (Dimitrov et al. 2003).

The RBMF is not well exposed east of the Sormany quarry, but steep dips in bedding and cleavage occur in the Nigadoo River Syncline and farther east in outcrops near the fault zone along the Nigadoo River (Walker et al. 1993a–c). No outcrop exists where the RBMF is inferred to transect the coastline south of the Nigadoo River mouth.

Both large- and small-scale oblique folds observed in the RBMF zone are consistent with models of dextral strike-slip deformation (*see* Sylvester and Smith 1988). North of Lower Tetagouche Lake and the RBMF lineament, calcareous rocks of the LaPlante Formation overlie redbeds of the Simpsons Field Formation on the northern limb of the Nigadoo River Syncline. This is the only location north of the fault where redbeds abut the RBMF. The single site south of the fault where redbeds of the Simpsons Field Formation abut the RBMF occurs on the east limb of the Murray Brook Anticline, about 30 km west of Lower Tetagouche Lake (Fig. 1a). These observations imply a post-Silurian, dextral offset of roughly 30 km along the RBMF.

Earlier authors also have suggested significant dextral offsets along the RBMF. Fyffe (1982) proposed one of 12 km, whereas van Staal and de Roo (1995) inferred a similar displacement of 60 km, based on the distance between Ordovician rocks of the Elmtree Inlier and correlative rocks of the Miramichi Highlands (inset of Fig. 1b). According to Walker et al. (1993c), about 1 km was the maximum dextral offset to have occurred after emplacement of the Middle Devonian Nicholas Denys Granodiorite (381 ± 4 Ma, Walker et al. 1991). Undeformed, flat-lying Carboniferous rocks have been mapped in the lineament of the RBMF near Middle Tetagouche Lake (Fig. 1a, b; Alcock 1941; Skinner 1974). These various studies collectively indicate that the RBMF underwent a long history of dextral motion, beginning after the deposition of Ordovician rocks and ending before the Late Carboniferous.

Northwesterly Trending Faults

Northwesterly trending faults are more numerous north of the RBMF, where both dextral and sinistral strike-slip offsets range from a few decimetres up to 60 m (Davies 1959; Davies et al. 1969). Many of these faults are tensional structures that host mineralization, such as the Nigadoo lode/vein sulphide deposit (Davies et al. 1969).

In the Sormany quarry, northwesterly trending faults are subparallel to the RBMF and exhibit brittle-ductile deformation (Dimitrov et al. 2003). One fault has a 50 m wide deformation zone that contains three subzones: 1) an exterior zone characterized by fault-drag folds and abundant small shear zones, and by fractures that commonly are conjugate and consistent with Riedel shear geometry, 2) a middle zone characterized by greater intensity of fracturing, incipient brecciation, and fragmentation of sheared sheath folds, and 3) an interior high-strain zone, where the rock is intensely fractured and brecciated. Larger fragments in the deformation

Figure 12. Fault mega-breccia associated with the internal high-strain zone of a northwest-trending strike-slip fault in the Sormany quarry. The view here is nearly perpendicular to the fault zone. It shows large, angular blocks of limestone and one block of shale (marked by arrow), surrounded by fault gouge. The location of this photograph is indicated on Figure 11.

zone are rotated and significantly displaced relative to one another such that the original texture of the rock is completely destroyed (Fig. 12).

The fault just described shows a dextral offset of 98 m and a predominantly strike-slip displacement. Its displacement mode is indicated by sheath folds containing horizontal hingelines, a piercing point (determined by the hingeline of a syncline), and a consistent cleavage orientation on both sides of the fault zone, showing no rotation in the fault plane. A second fault, located in the western part of the quarry, has a dextral offset of 15 m and a deformation zone that is about 3 m thick.

Vertical, northwesterly trending fractures reaching up to 300 m in strike length have been observed on the Chaleur Bay coastline north of Limestone Point. They are spaced as closely as 1.5 m, and their walls are undeformed. The fractures show little or no displacement and thus are categorized as joints. Erosion along these joints can produce topographic lineaments similar to those associated with true faults.

Small-scale Lineaments and Faults

Sets of small faults are exposed in rocks of the Simpsons Field Formation along the coast north of Pointe Rochette (Fig. 13). These fault sets occur in beds where pinch-and-swell structure is common, and locally they form an en échelon pattern. The faults vary in length from a few centimetres to several metres and show significant displacement of beds on a local scale. They are spaced several centimetres apart with no associated grain crushing, brecciation, kinking, or oblique conjugate fracturing.

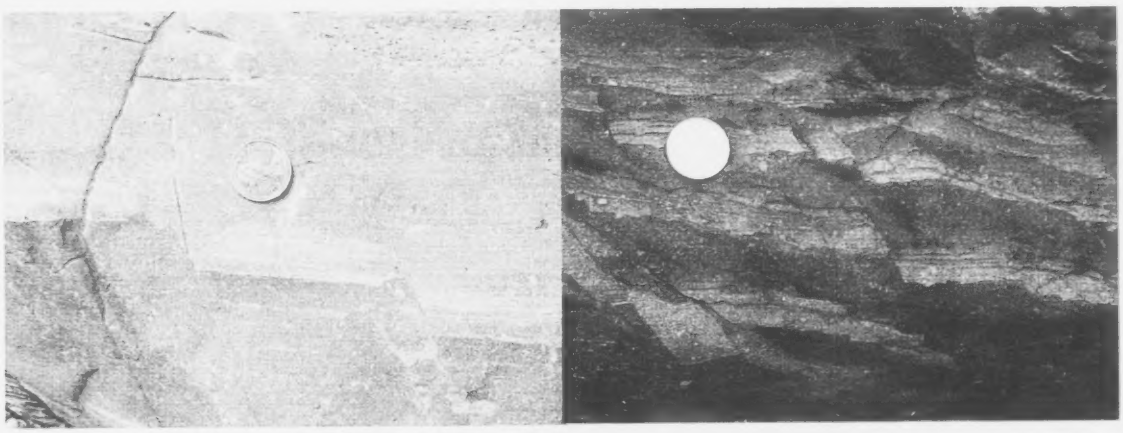

Figure 13. Sets of small faults in interbedded siltstone–shale of the Simpsons Field Formation north of Pointe Rochette. The scale of these faults is indicated by the quarter in the left photograph and the two-dollar coin in the right photograph.

The finely cleaved mudstones at the limestone–slate interface in the Sormany quarry contain a northeast-striking shear zone marked by intense cleavage (Dimitrov et al. 2003). The zone is about 500 m long and 1 to 3 m thick. It does not intersect the limestone but instead occupies the muddy transition zone between the calcareous LaPlante Formation and the siliciclastic Free Grant Formation. It is conformable with stratification and forms an enveloping surface above the reefal core.

On aerial photographs, this zone appears as a lineament indistinguishable from the many fault lineaments in the region (Fig. 11). Several electromagnetic profiles have been conducted across the structure with M31 handheld equipment. They reveal a V–shaped valley 5 to 15 m wide, 3 to 5 m deep, and filled with glacial sediments. The length of the lineament corresponds to the lateral extent of the limestone body.

The only cleavage direction observed in this zone is conformable with stratification. The cleavage strikes northeast at 40° to 50° and dips subvertically, resembling the regional cleavage

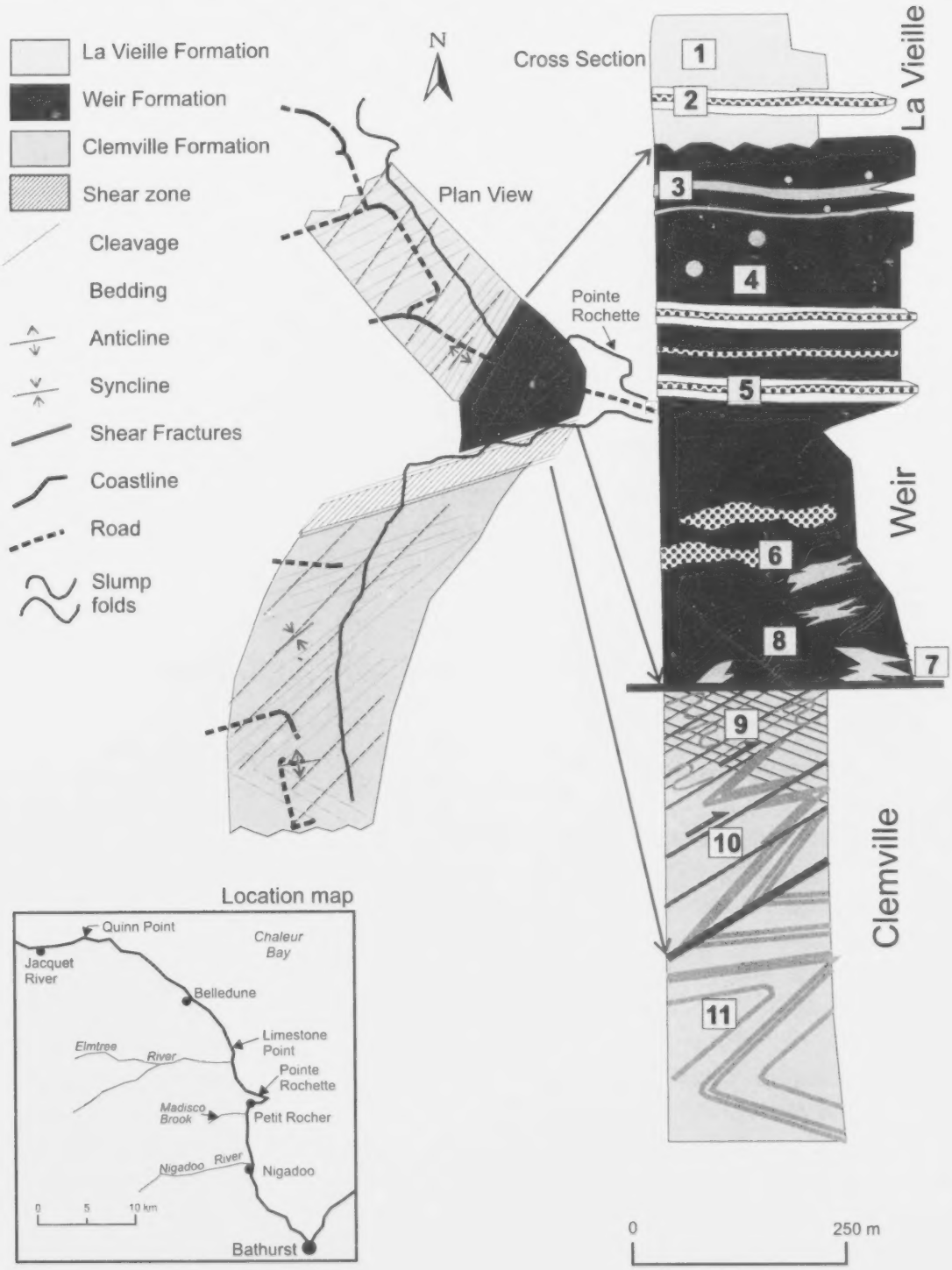

Figure 14. Simplified geology and structural map of Pointe Rochette, with plan view on left and expanded cross section on right. Explanatory notes for the numbered squares appear on the adjacent page. The location of this map is marked on Figure 2.

Notes to accompany Figure 14.

1. Dark grey, nodular limestone, and shale of La Vieille Formation.
2. Green, pebbly sandstone of La Vieille Formation.
3. Limestone beds of Weir Formation.
4. Corals, bryozoans, stromatoporoids, and other fossil fragments.
5. Lenses of grit and pebble conglomerate with inverse grading.
6. Irregular lenses and bed-like zones of pebble conglomerate with chaotic internal structure.
7. Lenses and drapes of green, distorted mudstones removed from underlying Clemville Formation by sedimentary rip-up.
8. Small, asymmetrical folds in lowest preserved beds of the Weir Formation.
9. Intensely deformed zone containing folds.
10. Spaced shear fractures, primarily subparallel to the cleavage or bedding. Amplitudes of displacement average several tens of centimetres.
11. Folded thin-bedded rocks of the Clemville Formation.

in orientation and appearance. Slickensides are exposed on the cleavage plane at the limestone–shale contact. Calcite fibre lineation on the slickensides indicates subvertical movement, suggesting that the southern block containing the reefal facies was uplifted relative to the northern block of the lineament zone.

Other zones of topographic depression have been mapped at the stratigraphic tops of competent reefal formations exposed in the Simpsons Brook area (Fig. 5). It is possible that the lithological contrast between calcareous bioherms and the overlying siliciclastic rocks served as the locus for fault development, but, to date, no reliable markers of displacement have been found.

Shear Zones of Uncertain Tectonic Origin

Two bands of intense deformation have been observed in coastal sections of the Clemville and Weir formations near Point Rochette. The first is a 5 m wide zone of disrupted greenish-grey rocks that are partly visible at the mouth of Madisco Brook. This exposure is too obscured to identify the nature of deformation.

The second, better exposed deformation zone occurs at the contact between the Weir and Clemville formations on Pointe Rochette (Fig. 2, 14). Unlike most faults in the region, the structure does not appear as a lineament on aerial photographs or satellite images and thus cannot be mapped away from the coastline. The shear zone is concentrated in the rhythmically interlayered calcisiltites and greenish-grey calcareous mudstones of the Clemville Formation (Fig. 14) and has an apparent thickness of about 70 m. The calcisiltite beds are folded and dismembered inside the mudstone, presumably as the result of postdepositional, differential shearing (Fig. 15a). The regional cleavage transects both limbs of some folds (F_1) but is axial planar to others (F_2). These fine-grained rocks of the Clemville Formation are in contact with

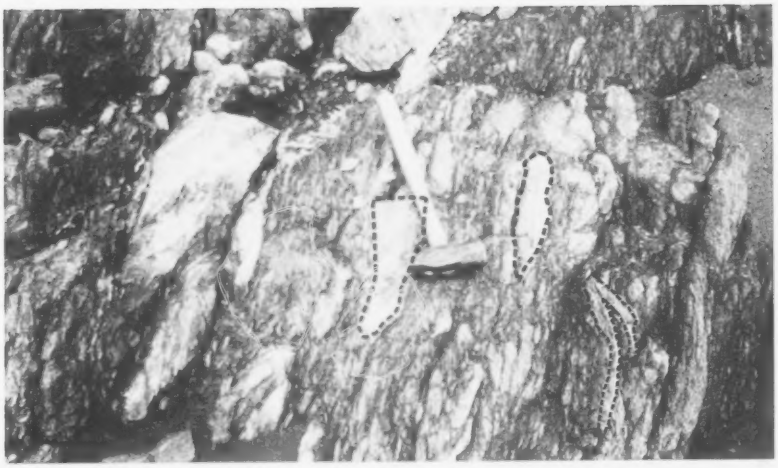

Figure 15a. Coastal rocks at Point Rochette, showing dismembered beds of the Clemville Formation underlying red pebbly sandstone of the Weir Formation. The hammer handle is 45 cm long.

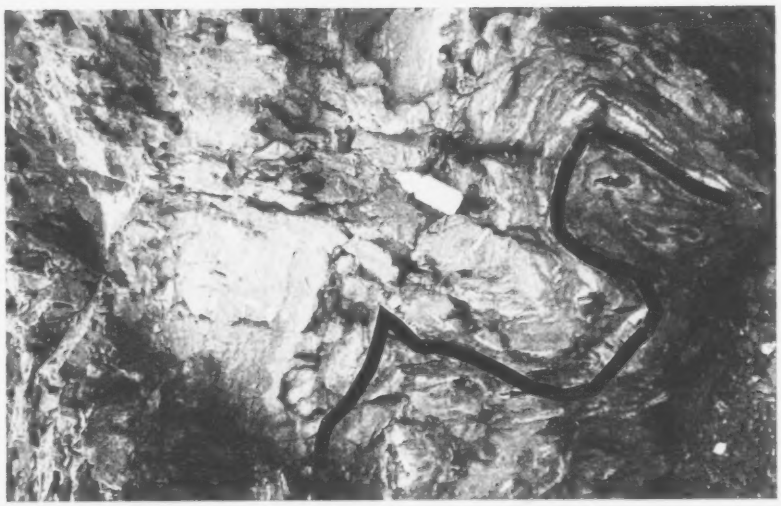

Figure 15b. Same location as Figure 15a. Shows a small fold in the deformed calcareous mudstone close to the base of the Weir Formation. The plastic bottle is 5 cm long.

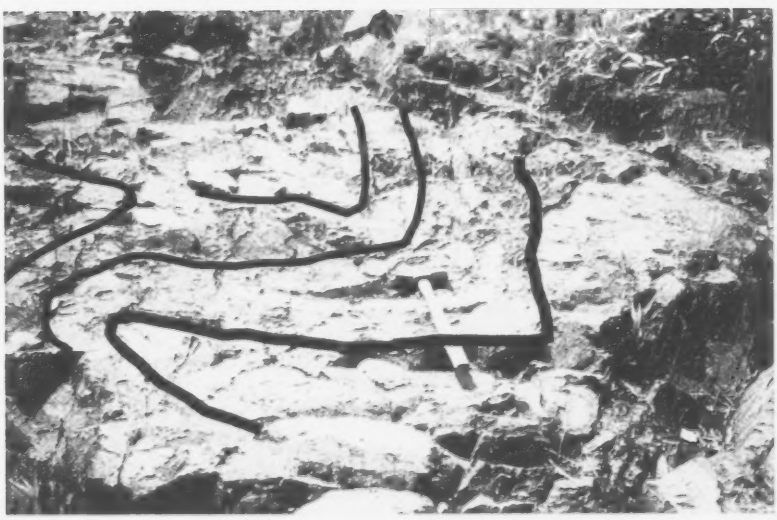

Figure 15c. Same location as Figure 15a. Shows folds in the lowest preserved beds of the Weir Formation, as revealed by differential weathering and alignment of poorly defined gravel layers. The hammer handle is 45 cm long.

red, matrix-supported, pebble conglomerate, grit, and sandstone of the Weir Formation to the north.

The deformation gradient begins in the lower part of the Weir Formation, appearing as spaced shear fractures that are grossly parallel to bedding and regional cleavage (Fig. 14). Moving down-section to the south, the number of spaced shears in the Weir Formation decreases, but a second set of closely spaced fractures intersects the regional cleavage at a high angle. The two directions of fissility give the rock a lumpy appearance. Moving farther down-section, the rocks break into structureless, earthy fragments. The cleavage planes intersect and displace each other. Bedding is disrupted and displaced, or bent into mesoscopic folds (Fig. 14, 15a–c). Major fractures filled with quartz and chlorite transect the lowest preserved beds of the Weir Formation but are not observed in the highly distorted beds of the adjacent Clemville Formation. In addition, lenses of greenish-grey mudstone from the underlying Clemville Formation appear in the Weir conglomerate, implying a process of sedimentary rip-up, whereby pebbly debris flows eroded and incorporated part of the basin floor.

Discussion and Conclusions

Rocks of the Chaleurs Group in the study area comprise a series of fluvial, shallow-water marine, and relatively deeper water facies that are key to interpreting the tectonic history of the region throughout the Silurian. Conglomeratic sequences of the Weir and Simpsons Field formations, and carbonate sequences of the La Vieille and LaPlante formations, collectively record two cyclic periods of tectonic uplift followed by relative stability.

The conglomerates and associated finer, siliciclastic rocks of the Weir Formation were deposited during uplift of the Elmtree Inlier above sea level during the late Llandovery. This was succeeded by a quiescent period featuring deposition of shallow-water limestone of the La Vieille Formation during the Wenlock, which completed the first cycle of uplift and stability. Later in the Silurian, deposition of the Simpsons Field strata reflected tectonic uplift of the Miramichi Highlands during the early Ludlow, and deposition of the LaPlante Formation strata recorded a subsequent quiescence during the Pridoli. The presence of limestone clasts in the Simpsons Field conglomerate suggests that an older limestone originally may have been present in the Highlands area. This possibly indicates that the initial uplift episode may have affected the Miramichi Highlands as well as the Elmtree Inlier.

In the Gaspésie and Maritime Appalachians, the age of the Silurian Salinic disturbance has been identified as primarily Pridoli. Yet unconformable relationships occur earlier in the stratigraphic record, in rocks of the late Wenlock (Bourque et al. 2000). In the study area, a Silurian unconformity occurs at the base of the Llandoverian Weir Formation in the Elmtree

Inlier, and at the base of the Ludlovian Simpsons Field Formation in the Miramichi Highlands to the southwest. In the Campbellton area of northern New Brunswick, a Late Silurian (Pridolian) unconformity exists at the base of the Lower Devonian Dalhousie Group (Wilson 2002). Rocks west of Campbellton in the Kedgwick area reveal no such Silurian unconformity (Carroll 2003).

These Silurian unconformities thus become progressively younger from east to west across New Brunswick until, by Kedgwick, they are no longer manifested in the stratigraphic record. Such unconformities of differing ages cannot reasonably be attributed to rising sea level, because sea levels remained high for most of the Silurian (Halam 1984; Algeo and Seslavinsky 1995). Instead, the diachronicity likely resulted from tectonic uplift of different blocks over an extended time period.

Syndepositional tectonic uplift in the late Llandovery (as evidenced by the Weir Formation) and early Ludlow (as evidenced by the Simpsons Field Formation) probably was achieved, or accompanied, by faulting. The faults responsible for uplift have since either been buried or, if still at surface, been overprinted by later fault motion. Fault control of sedimentation is inferred by indirect evidence such as 1) the alternating sequences of coarsening-thickening strata interbedded with fining-thinning strata, which may reflect rejuvenation of the depositional system after fault pulses (*see* Rust and Koster 1984; Eberly 1991), 2) the regional distribution of conglomeratic facies, and 3) the clast compositions of conglomerates, which reflect derivation from the nearby Ordovician basement.

Three categories of folds have been identified in the study area: pre-cleavage (F_1), cleavage-related (F_2), and fault-related (F_3). Faults occur in two major sets: one set trends northeasterly, and the other trends northwesterly. Faults with an early, pre-cleavage history of movement have been identified only at the scale of individual outcrops. Nonetheless, the widespread distribution of the Simpsons Field conglomeratic facies suggests that several late, regional-scale faults such as the RBMF also may have experienced earlier movement.

No reliable and universally accepted criteria exist for distinguishing faults formed under soft-sediment conditions from those formed by tectonic deformation. Small faults such as those in the Simpsons Field Formation north of Pointe Rochette (Fig. 13) are confined to specific stratigraphic intervals, which suggests that they accommodated extension parallel to the bedding. These faults may have formed under soft-sediment conditions in response to Llandoverian uplift of the Elmtree Inlier, or during a later tectonic event. Geometrically, they resemble extensional faults created in hard-rock experiments. The shear zone between the Weir and Clemville formations near Point Rochette (Fig. 14) may also represent an Early Silurian fault related to basin extension and sediment slumping. Such deformational features are consistent with the

fault-controlled basin model that Noble (1976) proposed to explain the rapid facies changes observed in the Silurian sequence of northeastern New Brunswick.

Postdepositional fault motions are easier to identify. Both the northwesterly and northeasterly trending faults cut and displace rocks of the Chaleurs Group, the regional Acadian cleavage, and the F_2 fold hinges. Offsets are larger on the northeasterly trending, kilometre-scale faults than on the northwesterly trending, metre-scale faults. Offset on the RBMF is dextral and by the Early Devonian may have reached a distance of up to 30 km. After emplacement of the Nicholas Denys Granodiorite in the Middle Devonian, however, dextral offset of the fault appears not to have exceeded 1 km. The northwesterly trending faults typically contain mineralization that is genetically related to Late Devonian granites (Davies et al. 1969; McCutcheon et al. 1992), which suggests that these faults originated during the Acadian Orogeny. On the other hand, northwesterly trending faults as young as Tertiary have been identified elsewhere in the Appalachian Orogen (Williams et al. 1995).

The F_1 folds are clearly pre-cleavage and appear to be confined to rocks older than the Simpsons Field Formation, giving the folds an age of pre-Ludlow. Thus, either the F_1 folding is pre-Salinic (assuming that the Salinic is a Pridolian event), or — as indicated by the stratigraphic evidence — the Salinic event is diachronous, being older in the study area than elsewhere in the Appalachians. The F_1 folds therefore could be related to tectonic uplift of the Elmtree Inlier and/or the Miramichi Highlands. Some F_2 folds are transected by the regional Acadian cleavage, possibly because of dextral motion along the RBMF. These folds are post-Salinic and are related mainly to the Acadian Orogeny. The post-regional-cleavage folds seem to be restricted to lithologies around the RBMF zone and may be post-Acadian. In the Gaspésie, northwesterly trending folds have been related to the Salinic disturbance, and northeasterly trending folds to the Acadian deformation (Bourque et al. 2000).

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NEW CHEMICAL DATA FROM NEOPROTEROZOIC–CAMBRIAN IGNEOUS ROCKS IN THE LONG REACH AREA, SOUTHERN NEW BRUNSWICK

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Igneous rocks in the Long Reach area of the New River Terrane consist of ca. 625 Ma mainly plutonic rocks of the Lingley Plutonic Suite, ca. 554 Ma mainly volcanic rocks of the Lobster Brook Formation, and undated felsic and mafic volcanic rocks interbedded with clastic sedimentary rocks of the Beulah Camp and Browns Flat formations. New geochemical data spanning these four units, combined with data from previous studies of volcanic rocks from the Beulah Camp and Browns Flat formations, have helped to better characterize igneous components of the units.

The Lingley Plutonic Suite is a compositionally expanded, I-type suite with characteristics that may be indicative of origin in a continental margin subduction zone. The Lobster Brook Formation is a dominantly felsic extrusive package with A-type chemical characteristics. The Beulah Camp Formation shows major- and trace-element trends similar to those in the Lingley Plutonic Suite, although the units are not likely to be of similar age. As shown in previous studies, the Browns Flat Formation is dominated by mafic volcanic rocks that appear to form two distinct chemical groups. One group consists of subalkalic basalt exhibiting high TiO_2, Fe_2O_3, P_2O_5, Zr, V, and Y, and low Al_2O_3 — a chemical signature typical of basalts formed in a within-plate tectonic setting. The second group displays chemical features atypical of such basalts, even though field associations suggest that the two groups are related. The highly altered nature of, and small sample set for, mafic rocks in the Beulah Camp Formation preclude a definitive correlation with other igneous rocks in the Long Reach area. Nonetheless, they are most similar to those of the Browns Flat Formation.

Les roches ignées du secteur de Long Reach du terrane de New River sont constituées de roches essentiellement plutoniques âgées d'environ 625 Ma du cortège plutonique de Lingley, de roches principalement volcaniques ayant environ 554 Ma de la Formation de

Lobster Brook, et de roches volcanomafiques et volcanofelsiques n'ayant pas fait l'objet de datation, interlitées avec des roches sédimentaires clastiques des formations de Beulah Camp et de Browns Flat. Les nouvelles données géochimiques couvrant ces quatre unités, conjuguées à des données d'études antérieures des roches volcaniques des formations de Beulah Camp et de Browns Flat, ont aidé à mieux caractériser les éléments ignés des unités.

Le cortège plutonique de Lingley constitue un cortège de type intrusif à composition élargie présentant des caractéristiques qui laissent supposer qu'il provient d'une zone de subduction de la marge continentale. La Formation de Lobster Brook représente un ensemble extrusif en prédominance felsique aux caractéristiques en fait d'éléments traces différentes de celles des roches felsiques de la Formation de Beulah Camp, supposée d'un âge similaire. Comme l'ont révélé des études antérieures, la Formation de Browns Flat constitue une formation à prédominance de roches volcanomafiques qui semble former deux groupes chimiques distincts. L'un de ces groupes est constitué de basalte subalcalin comportant de fortes concentrations de TiO_2, Fe_2O_3, P_2O_5, Zr, V et Y, et une faible concentration d'Al_2O_3 — un profil chimique typique des basaltes s'étant formés dans un cadre tectonique intra-plaque. Le second groupe présente des caractéristiques chimiques atypiques de ces basaltes, même si des observations de terrain laissent supposer que les deux groupes sont apparentés. La nature fortement altérée des roches mafiques de la Formation de Beulah Camp et l'ensemble d'échantillons restreint, empêchent l'établissement d'une corrélation définitive avec les autres roches ignées du secteur de Long Reach. Elles sont néanmoins très semblables aux roches de la Formation de Browns Flat.

INTRODUCTION

The Long Reach area of the lower Saint John River is situated within the New River Terrane (Johnson and McLeod 1996; Barr et al. 1999; Barr and White 2001). This northeast-trending, fault-bound terrane contains the most northerly exposures of Neoproterozoic rocks known in southern New Brunswick (Fig. 1).

The southwestern part of the terrane has been mapped by Johnson and McLeod (1996). Its northeastern section in the Long Reach area (Fig. 2) has been the subject of several studies during the last thirty years (e.g. McCutcheon 1981; Greenough et al. 1985; McCutcheon and Ruitenberg 1987; Tanoli and Pickerill 1988; Currie 1987, 1988, 1992, 2003; McLeod et al. 1994; Currie and McNicoll 1999). Contributions by these workers and more recently by Johnson (2001, 2003) have increased the knowledge of rock unit ages and relationships in this segment of the New River Terrane.

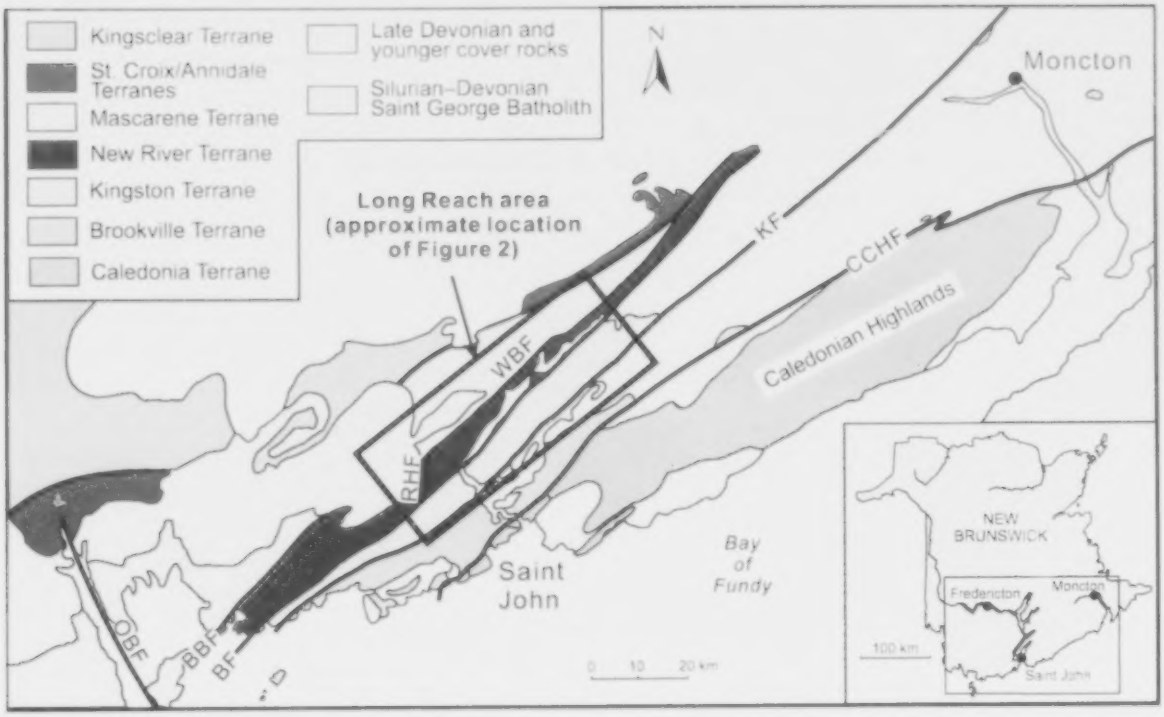

Figure 1. Terranes in southern New Brunswick showing the New River Terrane and the Long Reach area. BBF = Back Bay Fault, BF = Belleisle Fault, CCHF = Caledonia–Clover Hill Fault, KF = Kennebecasis Fault, OBF = Oak Bay Fault, RHF = Robin Hood Lake Fault, WBF = Wheaton Brook Fault.

The Robin Hood Lake Fault transects the central part of the New River Terrane. Johnson (2001, 2003) proposed the fault as a significant structural feature marking the boundary between two distinct tectonostratigraphic packages. She suggested that units in the Long Reach area northeast of the fault are affiliated with the Avalon Zone, whereas those southwest of the fault are possibly related to the Gander Zone (Williams 1995). In contrast, Barr and White (1996, 2001) suggested that Avalonian rocks in New Brunswick are restricted to east of the Caledonia–Clover Hill Fault (Fig. 1). Barr and White (1996), Johnson and McLeod (1996), van Staal et al. (1998), Fyffe et al. (1999), Barr et al. (2003), and references contained therein offer further descriptions of these terranes and their possible relationships.

To help resolve these controversies, Barr et al. (2003) compared Late Precambrian igneous units in the Caledonia, Brookville, and New River terranes. The study incorporated chemical analyses from the New River Terrane southwest of the Robin Hood Lake Fault, but lacked data from the terrane where it occurred in the Long Reach area. Published chemical analyses of selected volcanic rocks in the Long Reach area covered only small areas within the terrane (e.g. Greenough et al. 1985) or relied on a limited sample set (e.g. Currie 1992; Eby and Currie 1996).

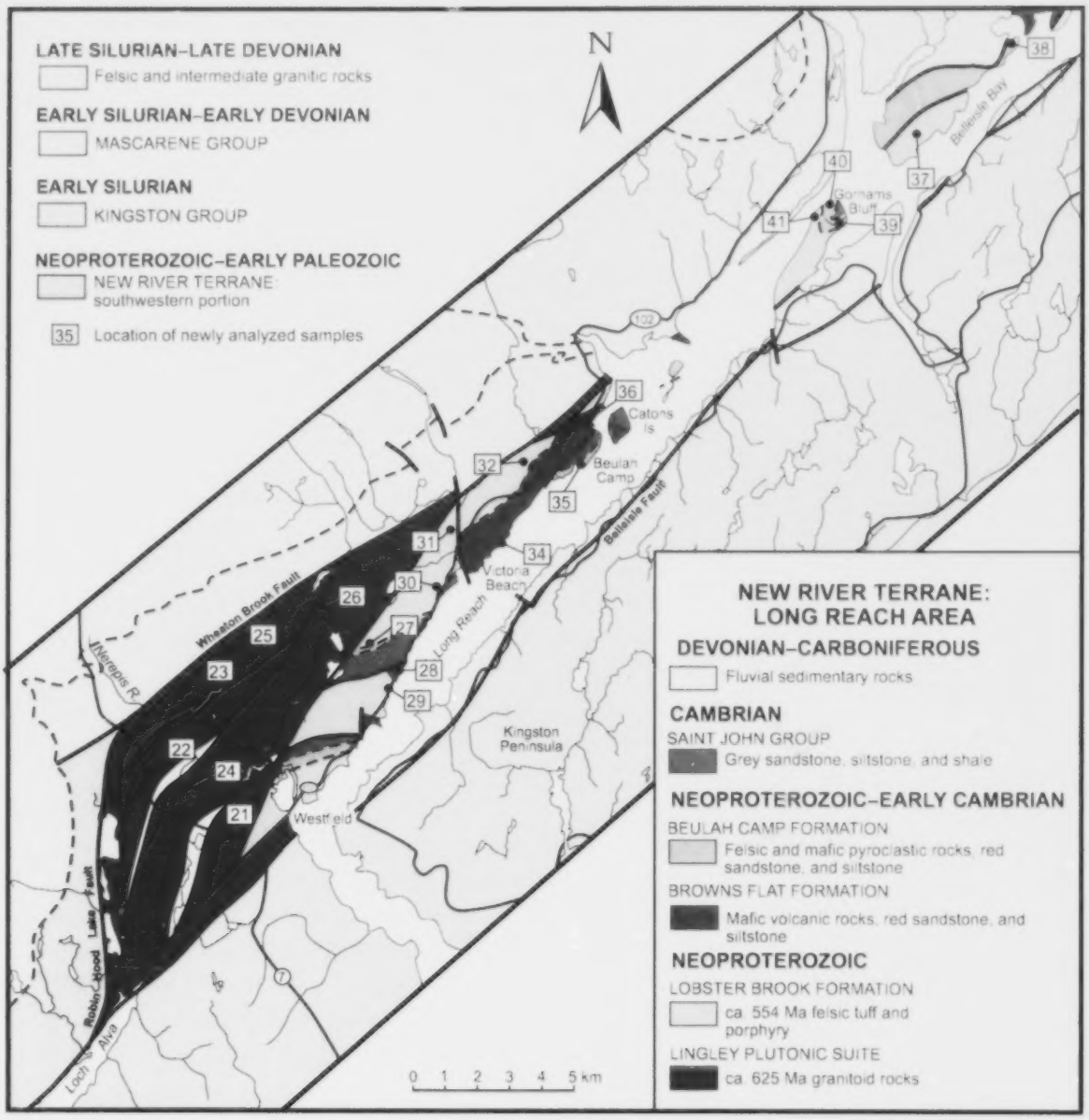

Figure 2. Geology map of the Long Reach area (modified after Johnson 2001) showing the location of newly analyzed samples.

The present study was conducted to analyze additional Neoproterozoic and Cambrian igneous rocks in the Long Reach area, thereby augmenting the chemical database of the New River Terrane. This paper reports the new information and offers a preliminary tectonic interpretation of results using both new and previously published chemical analyses.

GEOLOGICAL SETTING

The New River Terrane in the Long Reach area forms an attenuated, lozenge-shaped belt of rocks situated between the Wheaton Brook, Belleisle, and Robin Hood Lake faults (Fig. 1). The terrane extends along strike for about 50 km from the northeast end of Loch Alva northeastwards to Belleisle Bay (Fig. 2).

The stratigraphic succession in the Long Reach area comprises a suite of Neoproterozoic (ca. 625 Ma) felsic to intermediate plutonic rocks; Latest Neoproterozoic (ca. 554 Ma) rhyolite flows, tuff, and porphyry; probable Neoproterozoic to Cambrian mafic and felsic volcanic and sedimentary rocks; and fossiliferous rocks of the Cambrian Saint John Group (Fig. 2). The western termination of this succession is the north-south-trending Robin Hood Lake Fault, which shows a pronounced structural bend away from the northeast-trending Belleisle Fault. Several kilometres east of the Robin Hood Lake Fault, Neoproterozoic granitoid rocks and the younger rocks are tectonically interleaved within several north-south-trending, brittle fault slivers. Mylonitic fabrics usually seen in rocks of the New River Terrane west of the Robin Hood Lake Fault are noticeably absent in the Long Reach area. The following unit nomenclature and descriptions are after Johnson (2001).

Lingley Plutonic Suite

The oldest rocks in the Long Reach area belong to the Lingley Plutonic Suite (Johnson 2001), which forms a triangular wedge bound by the Wheaton Brook Fault to the north and the Robin Hood Lake Fault to the west (Fig. 2). This compositionally expanded suite consists primarily of medium- to coarse-grained plutonic rocks that include red leucogranite, granodiorite, tonalite, quartz diorite, quartz porphyry, quartz-feldspar porphyry, and rare felsic crystal tuff. The porphyry usually shows abundant small, rounded quartz phenocrysts.

The suite originally was termed the Lingley Pluton by Currie (1987), followed by McLeod et al. (1994), but later was subdivided into the Lingley and Brittain Creek plutons (Currie and McNicoll 1999). Intermediate and felsic intrusive rocks from the Brittain Creek and Lingley plutons yielded U–Pb ages of 625 ± 2 Ma and 629.3 ± 0.9 Ma respectively (Currie and McNicoll 1999). Currie and McNicoll described the latter sample as a greenish-ivory quartz-feldspar porphyry obtained from a Highway 7 roadcut about 2 km northwest of Lingley. They also interpreted small fragments of fine-grained felsic rocks and quartz sandstone in the porphyry as being cognate clasts (Currie and McNicoll 1999).

The Lingley Plutonic Suite is faulted to the east against the ca. 554 Ma Lobster Brook Formation. The suite shows complexly faulted relationships with other Neoproterozoic and younger units along Highway 7 between Westfield and the Nerepis River. In one of these fault

slivers, an unconformity is exposed between quartz ± feldspar porphyry of the Lingley Plutonic Suite and a probable Devono–Carboniferous red conglomerate (the Sagwa conglomerate of Johnson (2001)) that includes abundant basement clasts. The Sagwa conglomerate reportedly contains palynomorphs, indicating that it can be no older than Devonian (G. Dolby, written communication, 1998).

Lobster Brook Formation

The Lobster Brook Formation comprises extrusive and high-level intrusive rocks, including flow-banded ash tuff, rhyolite flows, felsic lithic-crystal tuff, rhyolite porphyry, and minor microgranite porphyry. These are found on the west side of Long Reach and to the northeast at Gorhams Bluff and along Belleisle Bay.

A rhyolitic ash tuff from Gorhams Bluff yielded a U–Pb age of 554 ± 6 Ma (Johnson 2001; McLeod et al. 2003), demonstrating that the Lobster Brook Formation is considerably younger than the Lingley Plutonic Suite. West of Long Reach, the Lobster Brook Formation is in fault contact with the Lingley Plutonic Suite (Fig. 2). Rhyolitic tuff and agglomerate of the Lobster Brook Formation are in contact with mafic volcanic rocks of the Browns Flat Formation on Route 102 west of Catons Island (Fig. 2). Although the contact is sheared, basalt fragments are incorporated into the rhyolitic tuff. As well, primary igneous layering in the Lobster Brook Formation locally appears to be concordant with bedding in maroon pyroclastic rocks resembling those of the Beulah Camp Formation, suggesting that these formations belong to a related sequence (Johnson 2001).

Beulah Camp Formation

The Beulah Camp Formation consists of 1) red rhyolitic to dacitic pyroclastic and epiclastic rocks, exposed at Beulah Camp on the western side of Long Reach, and 2) basalt and basaltic tuff, exposed at other locations in the Long Reach area and to the northeast at Gorhams Bluff and along Belleisle Bay (Fig. 2). Although undated, the formation in several localities appears to lie below grey sandstone of the Early Cambrian Saint John Group and hence is assumed to be Early Cambrian or even Neoproterozoic. McCutcheon (1981) and Greenough et al. (1985) observed the same relationship and considered the felsic pyroclastic rocks at Beulah Camp to be Early Cambrian.

As previously noted, bedding relationships between the Beulah Camp and Lobster Brook formations locally appear concordant; however, the Lobster Brook Formation is thrust over felsic volcanic rocks of the Beulah Camp Formation in the Belleisle Bay area. Red clastic sedimentary and mafic volcanic rocks in the Beulah Camp Formation are similar to those in the Browns Flat Formation, which indicates that they may be laterally equivalent.

Browns Flat Formation

Mafic volcanic and primarily red clastic sedimentary rocks of the Browns Flat Formation are exposed on the west side of Long Reach, mainly from Victoria Beach to Catons Island. They also occur in several faulted slivers along Highway 7 west of the Nerepis River (Fig. 2). Johnson (2001) assigned three informal members to the formation, which correspond approximately to map units C_1, C_2, and C_3 of Greenough et al. (1985). They comprise basaltic tuff, basalt, and mainly red sandstone and siltstone of the lower Gorham Road Member; red and grey sandstone, pebbly sandstone, siltstone, and shale of the Greenwich Hill Member; and basalt flows, sills, and red to grey siltstone of the upper Victoria Beach Member. As with the Beulah Camp Formation, the contact between the Browns Flat and Lobster Brook formations commonly is faulted or not exposed.

GEOCHEMISTRY

Lingley Plutonic Suite

The present study compares eight analyses of the Lingley Plutonic Suite: six new analyses (Fig. 2; Tables 1, 2) and two samples from Barr et al. (2003). Similarities in major- and trace-element composition between the leucomonzogranite sample (K98-399 from Barr et al. 2003) and the felsic tuff or subvolcanic intrusive sample (03SJ-21) suggest that, although little or no volcanic material has been preserved, the suite includes both extrusive and intrusive components.

The eight samples range from about 52 wt % SiO_2 (quartz diorite) to 78 wt % SiO_2 (leucomonzogranite). They demonstrate moderately to well-developed trends of decreasing TiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, and P_2O_5, and increasing K_2O with increasing SiO_2 (Fig. 3). Na_2O values uniformly plot close to 4 wt % and show no correlation with SiO_2 (Fig. 3f). Trends displayed by most major-element oxides are consistent with magmatic evolution related to crystal fractionation of major minerals (e.g. plagioclase and amphibole) in a comagmatic suite.

The initial increase of Al_2O_3 in the dioritic to tonalitic samples is consistent with a high modal plagioclase content, which indicates that the samples did not undergo feldspar fractionation. As with K_2O and CaO, respectively, Ba and Rb increase and Sr decreases with increasing SiO_2, although all values show wide scatter, especially Sr (Fig. 4a–c). Elements compatible in mafic minerals, such as V, display a fairly smooth decrease with increasing SiO_2 (Fig. 4d). By contrast, incompatible trace elements Nb, Y, and Zr are scattered and show no systematic correlation with SiO_2 (Fig. 4e–g). Metals such as Cu and Zn (Fig. 4h, i) are low throughout the suite.

Table 1. Locations and petrographic descriptions of newly analyzed samples.

Sample #	Rock Unit	Lat.	Long.	Rock Name	Petrographic Description
03SJ-21	Lingley Plutonic Suite	45 21 40	66 15 51	felsic crystal tuff	Cg to fg clasts of embayed qtz, plag, & K-spar in very fg felsic ash groundmass, with irregular patches & stringers of coarser qtz-felds crystals. Abundant hematite.
03SJ-22	Lingley Plutonic Suite	45 22 34	66 17 30	tonalite	Cg plag & qtz; <2% completely chloritized bt; scattered large titanite grains; intense sauss of plag; brecciated with carbonate veining.
03SJ-23	Lingley Plutonic Suite	45 24 07	65 16 39	leuco-monzogranite	Cg plag, qtz & interstitial granophyre; very altered to saussurite & sericite.
03SJ-24	Lingley Plutonic Suite	45 22 34	66 16 35	monzogranite	Mg plag, qtz, K-spar, chloritized bt; hypidiomorphic granular with interstitial K-spar.
03SJ-25	Lingley Plutonic Suite	45 25 22	66 14 28	diorite	Fg plag & secondary chlorite & epidote (after amphibole?); hypidiomorphic granular to intergranular texture; epidote & carbonate patches & veins.
03SJ-26	Lingley Plutonic Suite	45 25 36	66 13 40	quartz diorite	Mg plag, green/brown amphibole, relict cpx, minor interstitial qtz; hypidiomorphic granular texture; scattered ilmenite. Pervasive epidotization in mafic minerals & plag.
03SJ-27	Lobster Brook Formation	45 24 50	66 12 23	rhyolite	Fg allotriomorphic granular groundmass of quartz, K-spar, & plag; locally spherulitic; sparse embayed qtz phenocrysts, abundant hematite.
03SJ-29	Lobster Brook Formation	45 24 02	66 12 01	rhyolite	Similar to above but coarser grained groundmass.
03SJ-30	Lobster Brook Formation	45 26 15	66 10 30	rhyolite	Similar to above but coarser grained groundmass; scattered feldpsar phenocrysts pseudomorphed by carbonate & albite.
03SJ-31	Lobster Brook Formation	45 26 53	66 10 30	rhyolite	Similar to above but coarser grained groundmass; more albitized feldspar.
03SJ-32	Lobster Brook Formation	45 28 03	66 08 43	rhyolite tuff	Fg felsic groundmass & scattered clasts of qtz & feldspar. Eutaxitic banding in places & felsic lithic clasts.
03SJ-37	Lobster Brook Formation	45 33 56	65 59 30	rhyolite	Fg allotriomorphic granular groundmass of quartz, K-spar & plag; brecciated & very altered to sericite & hematite.
03SJ-41	Lobster Brook Formation	45 32 26	66 02 05	rhyolitic tuff	Cg to fg clasts of embayed qtz, plag & K-spar in very fg felsic ash groundmass, with irregular patches & stringers of coarser qtz-feldspar crystals. Scattered biotite flakes. Abundant hematite.
03SJ-35	Beulah Camp Formation	45 28 03	66 07 27	dacitic lithic-crystal tuff	Mainly mg plag & larger lithic (dacitic) clasts in a hematite-rich feldspar-qtz matrix.
03SJ-39	Beulah Camp Formation	45 32 21	66 01 23	basalt	Fg pilotaxitic plagioclase; scattered amygdales filled by chlorite; scattered pyroxene & plag (?) phenocrysts pseudomorphed by magnetite/hematite & albite.
03SJ-40	Beulah Camp Formation	45 32 34	66 01 25	basalt	Fg intergranular to intersertal plag & secondary minerals after cpx; abundant carbonate patches & veins.
03SJ-38	Beulah Camp Formation	45 35 17	65 57 26	basaltic tuff	Abundant basaltic clasts varying in texture from cryptocrystalline to mg. Plag abundant in clasts & groundmass.
03SJ-28	Browns Flat Formation (Victoria Beach Member)	45 24 21	66 11 52	basalt	Fg intergranular to intersertal plag & cpx; secondary chlorite & epidote; local pilotaxitic plag laths; scattered amygdales with carbonate & zeolite.
03SJ-34	Browns Flat Formation (Victoria Beach Member)	45 26 35	66 09 29	basalt (sill?)	Fg intergranular to intersertal plag & cpx; scattered olivine phenocrysts completely pseudomorphed by chlorite & serpentine.
03SJ-36	Browns Flat Formation (Gorham Road Member)	45 28 53	66 07 25	basalt	Fg intergranular to intersertal plag & cpx; scattered plag phenocrysts; abundant secondary epidote, hematite, chlorite, pumpellyite.

Notes: bt = biotite, cg = coarse-grained, cpx = clinopyroxene, fg = fine-grained, K-spar = alkali feldspar, mg = medium-grained, plag = plagioclase, qtz = quartz, sauss = saussuritized.

The Lingley Plutonic Suite as a whole is subalkalic (Fig. 5a), but evidence for its tectonic setting is inconclusive. Some samples plot distinctly within the volcanic-arc field on the Rb vs Y + Nb discrimination diagram (Fig. 5b), yet the most felsic samples of the suite overlap into the within-plate granite field. High Zr content in some samples indicate an A-type affinity, although the Ga–Al ratio generally is lower than that of typical A-type granites (Fig. 5c).

Only the quartz diorite sample (03SJ-26) has a SiO_2 content low enough to be plotted on mafic discrimination diagrams. It falls in the within-plate field of the V vs Ti diagram (Fig. 5d), but shows a calc-alkalic affinity on the Zr vs Ti vs Y ternary discrimination diagram (Fig. 5e). It also plots in the volcanic-arc basalt/within-plate tholeiite field on Figure 5f. Although the tectonic setting of the Lingley Plutonic Suite is unclear, its compositionally expanded nature is most consistent with formation in a continental margin subduction zone.

Lobster Brook Formation

The present study compares twelve analyses of the Lobster Brook Formation. These comprise seven new analyses of rhyolite flow and tuff samples (Fig. 2; Tables 1, 2), four analyses of quartz-feldspar porphyry samples collected from Route 102 west of Long Reach by Eby and Currie (1996), and one analysis of the Gorhams Bluff dating locality mentioned earlier (Johnson 2001; McLeod et al. 2003).

All analyzed samples are felsic with SiO_2 contents that range from 74 to 80 wt % recalculated volatile-free (Fig. 3). Samples of the Lobster Brook Formation show trends of decreasing Al_2O_3 and Na_2O (Fig. 3b, f), which implies fractionation of albitic plagioclase. K_2O displays no consistent trend (Fig. 3g), suggesting that alkali feldspar may not have been removed. Ba and Rb show a broad spread, as does K_2O, whereas Sr (like CaO) decreases to low values in samples containing the highest SiO_2 (Fig. 4a–c). Metal concentrations are low (Fig. 4d, h, i). Zr and Y display wide variation, whereas Nb does not (Fig. 4e–g).

All samples plot in the rhyodacite/dacite and rhyolite (granodiorite–granite) fields on the Zr/TiO_2 vs Nb/Y diagram (Fig. 5a). Most samples show a moderate Ga–Al ratio and elevated Zr content, suggesting A-type affinity (Fig. 5c). Trace-element ratios here suggest a within-plate tectonic environment, although some samples plot in the volcanic-arc field (Fig. 5b).

Beulah Camp Formation

The present study compares seven analyses of the Beulah Camp Formation. These consist of three felsic samples collected along the shore at Beulah Camp by Greenough et al. (1985), and four new analyses (Fig. 2; Tables 1, 2): three basaltic samples from the Belleisle Bay area, and one dacitic tuff from the south side of the wharf at Beulah Camp (Fig. 2).

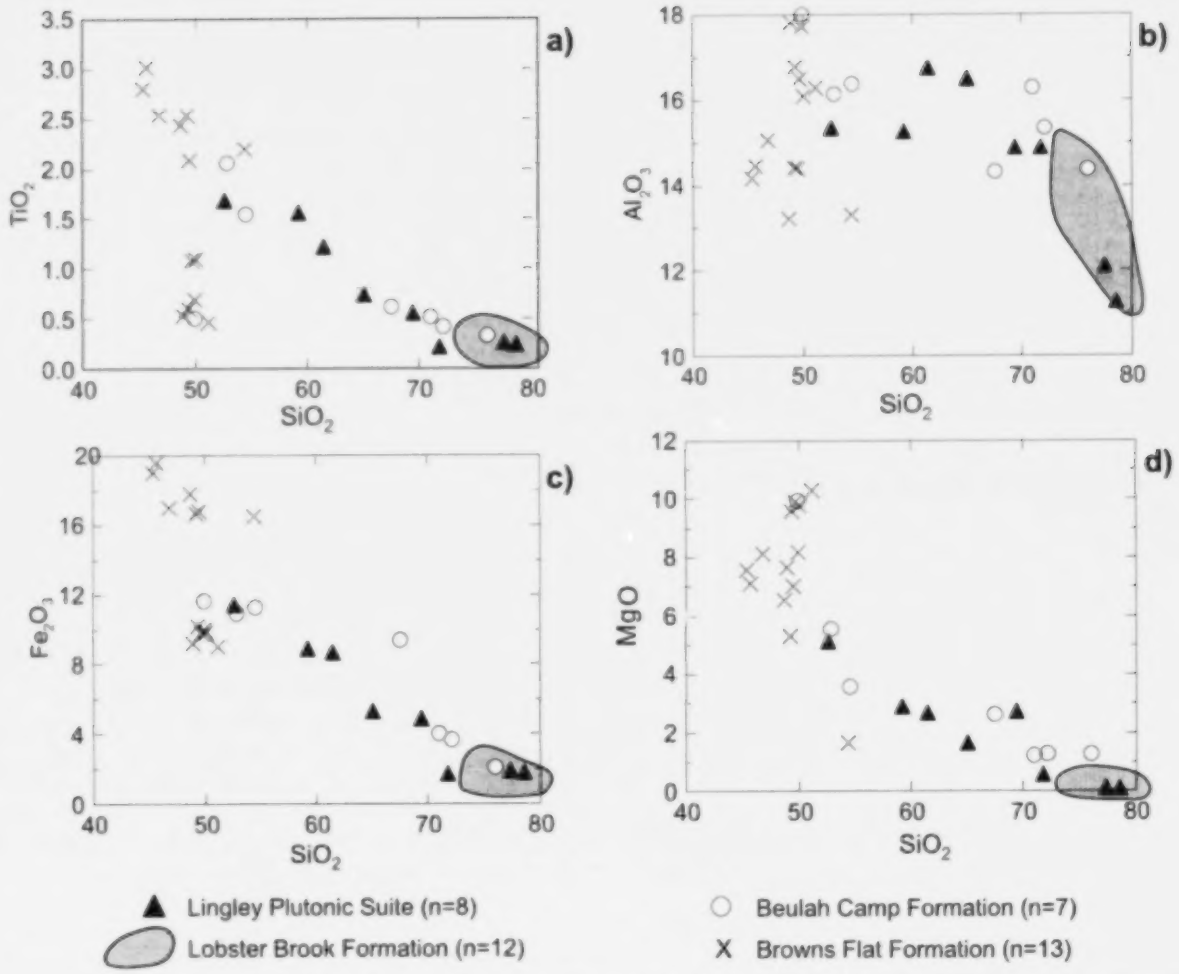

Figure 3. Major element oxides (wt %) vs SiO_2 (wt %) showing chemical variation in analyzed samples.

In chemical composition, the four felsic samples generally resemble samples with similar SiO_2 values from the Lingley Plutonic Suite (Fig. 3, 4). They differ from the Lobster Brook Formation in having higher MgO and Sr (Fig. 3d, 4c), a lower Zr–TiO_2 ratio (Fig. 5a), and lower K_2O, Rb, Nb, and Zr (Fig. 3g, 4b, e, g). It is difficult to assess the significance of these differences, given the limited number of samples. Rocks of the Beulah Camp Formation compositionally resemble the Lingley Suite, although their ages are unlikely to be similar. As with the Lingley Plutonic Suite samples, the Beulah Camp felsic samples span the volcanic-arc and within-plate fields (Fig. 5b), and the I/S-type and A-type granite fields (Fig. 5c).

The three mafic samples show a narrow range in SiO_2 content (49–54 wt %) but a wide range in values of other major-element components, especially TiO_2, MgO, and CaO (Fig. 3a, d, e). These samples are highly altered, and their large loss-on-ignition values (5–10 wt %) reflect abundant carbonate material. Hence, chemical analyses may not be reliable indicators of original igneous characteristics. As well, the number of samples is too small for reliable assessment.

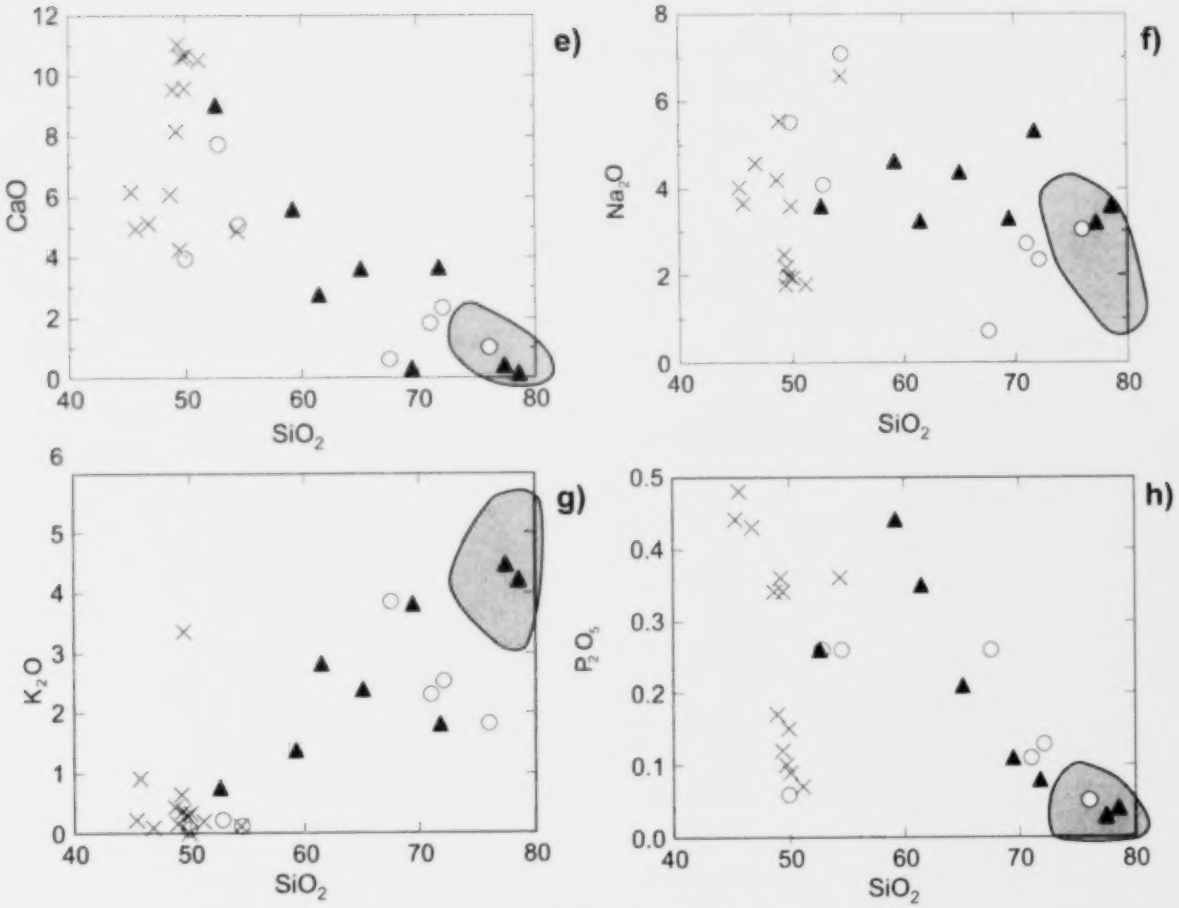

Figure 3 (cont'd). Major element oxides (wt %) vs SiO_2 (wt %).

Keeping these limitations in mind, it is suggested that the three samples appear to be subalkalic (Fig. 5a) but display what may be tholeiitic characteristics (Fig. 5d–f). As discussed below, the two Gorhams Bluff basalt samples (Fig. 2; Tables 1, 2) show a striking contrast in values for relatively immobile elements such as Ti, Zr, Nb, and Y.

Browns Flat Formation

The present study compares thirteen analyses of the Browns Flat Formation. These comprise three new analyses of basaltic samples (Fig. 2; Tables 1, 2) and ten analyses of samples collected by Greenough et al. (1985). The geochemical data show a wide range of values for loss-on-ignition (2.3–10 wt %) and for several chemical components. Recalculated SiO_2 values range from about 45 to 55 wt % (Fig. 3). Two samples of the Victoria Beach Member (03SJ-28, 03SJ-34) and the one sample of the Gorham Road Member (03SJ-36) show chemical data that are consistent with values from Greenough et al. (1985).

The Browns Flat Formation samples can been divided into two groups based on their component analyses, although features of the groups are not entirely consistent. The Gorham Road Member has

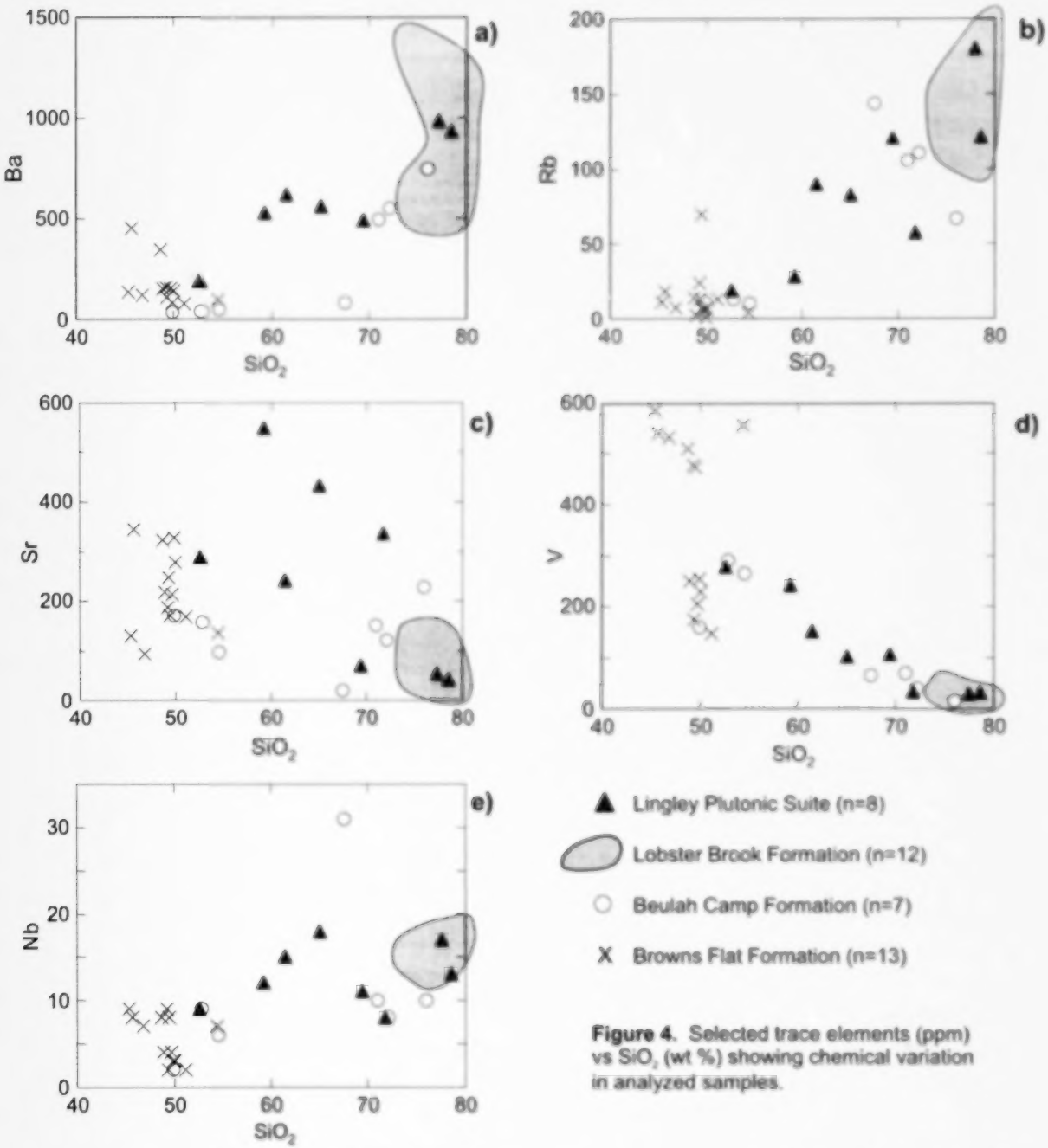

Figure 4. Selected trace elements (ppm) vs SiO_2 (wt %) showing chemical variation in analyzed samples.

low Al_2O_3, and high TiO_2, Fe_2O_3, P_2O_5, Zr, V, and Y when compared with basaltic rocks of the Victoria Beach Member. Both groups are subalkalic and, on some diagrams, plot mainly in the arc or calc-alkalic fields (e.g. Fig. 5e, f). Yet the Gorham Road and Victoria Beach members plot as two distinct groups on the V vs Ti diagram (Fig. 5d), appearing in the upper right and lower left quadrants, respectively. The Gorham Road Member plots definitively in the within-plate tholeiite field, whereas the Victoria Beach Member is transitional between the arc and within-plate fields.

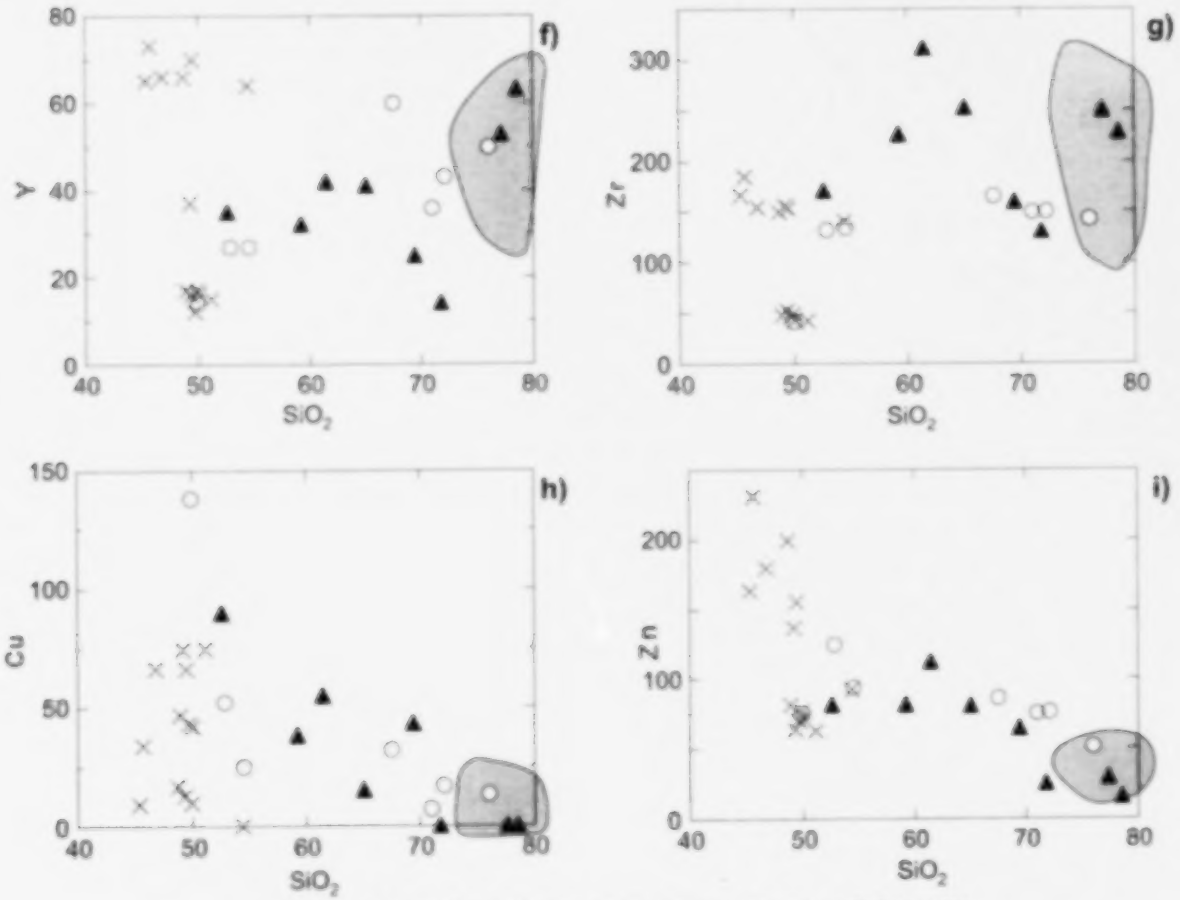

Figure 4 (cont'd). Selected trace elements (ppm) vs SiO_2 (wt %).

Discussion and Conclusions

This paper presents geochemical data for the four main units in the Long Reach area: the Neoproterozoic Lingley Plutonic Suite (ca. 625 Ma), the Neoproterozoic Lobster Brook Formation (ca. 554 Ma), and the Neoproterozoic or Early Cambrian Beulah Camp and Browns Flat formations. These chemical data are not especially useful for characterizing the tectonic setting of the four units, owing to the small data set and limited compositional variation in some units. Nonetheless, several broad comparisons can be made.

The compositionally expanded nature of the Lingley Plutonic Suite suggests that it formed in a continental margin subduction zone. This is consistent with the tectonic setting proposed for rocks of similar age elsewhere in southern New Brunswick (e.g. Barr et al. 2003). The lack of mafic rocks in the Lobster Brook Formation and its uncertain tectonic setting make it difficult to state definitively how the formation compares to bimodal, within-plate volcanic and plutonic sequences beyond the New River Terrane (Barr and White 1996). The two most felsic samples of the Lingley Plutonic Suite, and the felsic volcanic to subvolcanic rocks of the Lobster Brook Formation, differ in age but show similar major-element and trace-element compositions.

Table 2. New chemical data for samples from the Long Reach area.

03SJ Sample #	21	22	23	24	25	26	27	29	30	31	32	37	41	35	38	39	40	28	34	36
Rock Unit	LP	LP	LP	LP	LP	LP	LB	LB	LB	LB	LB	LB	LB	BC	BC	BC	BC	BFVB	BFVB	BFGR
wt %																				
SiO_2	76.58	62.27	68.33	67.56	57.19	51.49	76.69	76.96	78.22	80.18	72.94	79.30	71.74	69.06	51.64	46.59	47.62	49.00	48.50	47.47
TiO_2	0.26	0.70	0.21	0.53	1.51	1.64	0.26	0.22	0.19	0.17	0.25	0.24	0.41	0.50	1.47	0.47	1.86	0.45	0.60	2.44
Al_2O_3	11.94	15.76	14.17	14.49	14.73	15.01	12.03	11.82	12.55	11.51	14.73	11.12	12.70	15.84	15.5	16.8	14.54	15.59	16.47	13.9
Fe_2O_3	1.95	5.1	1.66	4.76	8.62	11.18	1.93	1.50	1.36	1.45	1.29	1.37	2.59	3.89	10.67	10.88	9.83	8.69	10.01	16.04
MnO	0.03	0.14	0.05	0.07	0.16	0.20	0.03	0.11	0.03	0.03	0.02	0.04	0.06	0.05	0.2	0.39	0.18	0.15	0.17	0.22
MgO	0.09	1.58	0.52	2.63	2.80	5.00	0.09	0.19	0.07	0.07	0.12	0.12	0.25	1.18	3.39	9.28	5.02	9.84	9.4	5.11
CaO	0.50	3.46	3.51	0.29	5.39	8.85	0.50	0.87	0.74	0.17	1.12	0.32	1.92	1.76	4.8	3.7	6.99	10.11	10.87	7.9
Na_2O	3.17	4.18	5.06	3.21	4.46	3.51	3.19	0.95	1.48	1.21	3.85	1.91	2.44	2.66	6.71	5.14	3.66	1.74	1.76	2.4
K_2O	4.47	2.29	1.72	3.70	1.33	0.74	4.46	4.21	4.86	5.25	4.19	4.53	3.72	2.25	0.11	0.06	0.19	0.18	0.36	0.62
P_2O_5	0.03	0.2	0.08	0.11	0.42	0.25	0.04	0.02	0.02	0.02	0.02	0.03	0.08	0.11	0.25	0.06	0.24	0.07	0.12	0.35
LOI	0.70	3.63	3.8	1.90	3.00	2.10	1.30	2.06	1.70	1.09	1.70	1.00	2.96	2.1	4.9	6.4	9.9	4.4	2.3	3.56
Total	99.73	99.32	99.1	99.25	99.61	99.97	100.52	98.91	101.21	101.15	100.23	99.98	98.88	99.40	99.64	99.77	100.03	100.21	100.56	100.01
ppm																				
U	5	2	1	3	< 1	< 1	5	5	5	5	5	5	4	3	< 1	< 1	1	< 1	< 1	< 1
Th	15	7	< 2	14	8	4	20	20	15	15	23	21	18	3	5	4	2	< 2	4	2
Zr	255	252	131	160	226	171	250	144	212	191	228	267	231	149	134	42	132	43	53	156
Nb	17	18	8	11	12	9	18	18	18	18	16	19	15	10	6	2	9	2	2	9
Rb	166	83	58	121	28	19	177	158	182	201	147	152	143	106	10	11	13	13	13	24
Ba	970	558	1528	489	526	190	929	595	552	745	1385	1133	662	495	50	32	41	77	110	157
Sr	44	433	336	69	548	288	43	14	8	19	122	54	38	151	97	171	158	169	248	188
Ni	149	< 3	< 3	16	8	19	6	< 3	< 3	3	< 3	< 3	14	5	8	139	41	212	154	57
Cr	49	< 4	< 4	37	< 4	42	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4	15	621	144	704	366	64
Co	62	32	35	45	44	65	37	39	43	53	34	45	39	26	56	70	54	56	59	75
V	25	102	33	106	240	278	29	23	19	17	27	25	49	69	264	159	290	146	175	478
Y	53	41	14	25	32	35	31	50	58	66	51	67	46	36	27	14	27	15	16	37
Cu	< 4	15	< 4	43	38	90	4	17	< 4	< 4	< 4	< 4	15	7	25	138	52	74	13	74
Zn	31	81	25	65	82	82	31	36	36	41	38	34	38	75	94	75	125	63	64	136
Ga	14	19	16	14	19	17	12	14	15	13	14	10	14	19	21	14	15	15	15	18
Pb	9	11	9	14	14	15	10	75	22	41	26	53	31	23	13	33	90	4	< 3	44
La	39	29	16	34	31	13	47	60	50	64	41	85	28	23	7	< 5	20	8	< 5	10
Nd	33	27	19	29	29	23	37	46	43	51	33	59	23	25	12	< 5	24	15	15	16

Notes: 1. Fe_2O_3 = total Fe expressed as Fe_2O_3, LOI = Loss on Ignition, LP = Lingley Plutonic Suite, LB = Lobster Brook Fm, BC = Beulah Camp Fm, BFVB = Browns Flat Fm - Victoria Beach Member, BFGR = Browns Flat Fm - Gorham Road Member.

2. Analyses conducted by X-ray fluorescence in the Nova Scotia Regional Geochemical Facility, St. Mary's University, Halifax, Nova Scotia. More detailed information available at http://www.stmarys.ca/academic/science/geology/geology/rgc/rgc_home.htm

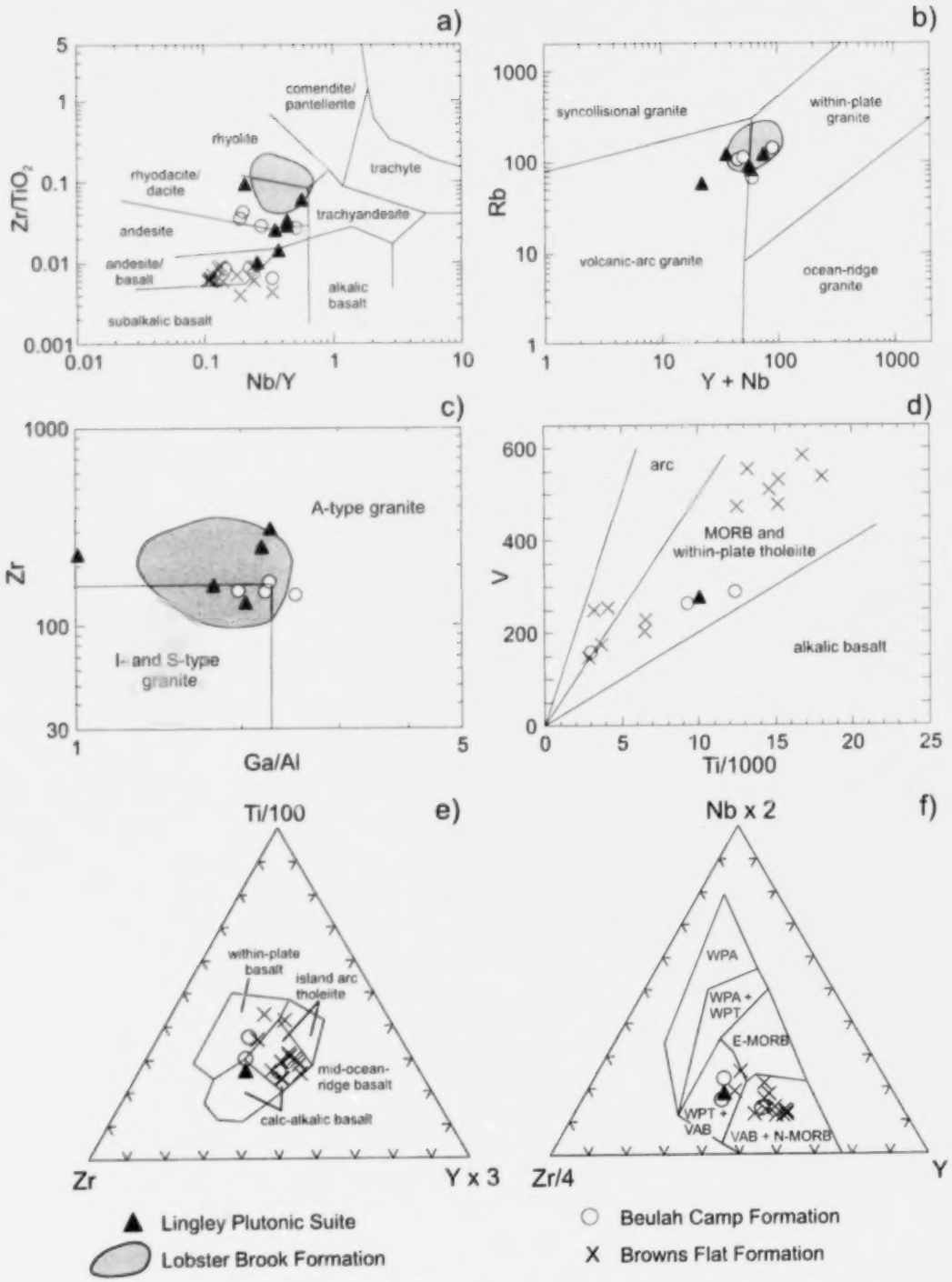

Figure 5. Discrimination diagrams for chemical affinity and tectonic setting.
a) Zr/TiO_2 vs Nb/Y with volcanic rock fields from Winchester and Floyd (1977).
b) Samples with >60% SiO_2 plotted on Rb vs Y + Nb diagram from Pearce et al. (1984).
c) Samples with >60% SiO_2 plotted on Zr vs Ga/Al diagram from Whalen et al. (1997).
d) Samples with <55% SiO_2 plotted on V vs Ti diagram with fields from Shervais (1982).
e) Samples with <55% SiO_2 plotted on Ti–Zr–Y ternary diagram from Pearce and Cann (1973).
f) Samples with <55% SiO_2 plotted on Nb–Zr–Y diagram from Meschede (1986).
WPA = within-plate alkalic basalt, WPT = within-plate tholeiitic basalt, VAB = volcanic-arc basalt, N-MORB = normal mid-ocean-ridge basalt, E-MORB = enriched mid-ocean-ridge basalt.

Felsic volcanic rocks of the Lobster Brook and Beulah Camp formations have dissimilar major- and trace-element concentrations (Fig. 3, 4). Conversely, felsic rocks of the Beulah Camp Formation show major- and trace-element trends that markedly resemble those of the Lingley Plutonic Suite. The Beulah Camp Formation has not been dated, but it is interpreted as being Latest Neoproterozic to Early Cambrian on the basis of stratigraphic position (Johnson 2001). Although the formation appears to lie below late Early Cambrian strata, its maximum age is less well constrained. Mafic rocks of the Beulah Camp and Browns Flat formations exhibit the same contrast in relatively immobile elements such as Ti, Z, and Y, which is consistent with their lithological resemblances. These chemical and lithological similarities suggest that basaltic rocks in the Beulah Camp and Browns Flat formations may be laterally equivalent.

Mafic rocks in both units form two distinct groups in terms of their chemical components (Fig. 3, 4). Greenough et al. (1985) demonstrated that the groups show similar trends on rare-earth-element plots and suggested that low-pressure fractionation could explain differences between the high- and low-Ti basalts. The presence of highly unevolved basaltic rocks in both formations make it tempting to suggest that they formed in an arc setting, especially because felsic rocks in the Beulah Camp Formation exhibit chemical similarities to those in the Lingley Plutonic Suite.

Greenough et al. (1985), however, proposed a different interpretation. They reasoned that, although some basalts plotted in the field of ocean-floor basalt, slopes of the rare-earth-element patterns lay within the range of basalts from several tectonic settings. Greenough et al. (1985) suggested that chemical characteristics of the Browns Flat Formation resembled those of Mesozoic continental rift basalts in Atlantic Canada (*also see* Pe-Piper et al. 1992) and hypothesized a similar tectonic setting for rocks in the Long Reach area.

Overall, no compelling indication of tectonic setting emerges from the chemical data. Additional field work, chemical analyses, and especially U–Pb dating are needed to resolve geological complexities in the Long Reach area.

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POTENTIAL USES OF SURFICIAL MAPPING DATA FOR REGIONAL PLANNING IN NEW BRUNSWICK

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Since the 1950s, surficial mapping in New Brunswick has made significant contributions to the fields of mineral exploration and groundwater research. Preliminary surficial data from the Caledonian Highlands area, southeastern New Brunswick, was used in the mid-1990s to assist in compiling a forest soils map for the province. Subsequent work in the Caledonian Highlands has enabled researchers to develop more complex surficial mapping units — ones that incorporate a broader range of information and result in surficial maps with wider practical applications. The recent completion of surficial mapping over large, continuous regions of New Brunswick has produced a comprehensive database designed for use by a range of disciplines. The information can be (and in some cases already has been) integrated into maps for regional planning, hazard potential determination, and the modelling of forest soil hydrology.

Les travaux de cartographie de surface au Nouveau-Brunswick ont contribué de façon appréciable aux domaines de l'exploration minérale et de la recherche sur les eaux souterraines depuis les années 50. Tout récemment, les données superficielles préliminaires du secteur des collines calédoniennes du Sud-Est du Nouveau-Brunswick ont servi à la compilation d'une carte des sols forestiers de la province. Des travaux subséquents dans les collines calédoniennes ont permis aux chercheurs de mettre au point des unités de cartographie de surface plus complexes, c'est-à-dire des unités qui incorporent un éventail plus vaste de données et qui procurent des cartes des dépôts meubles permettant des applications pratiques plus vastes. La réalisation récente de travaux de cartographie de surface couvrant des régions étendues et continues du Nouveau-Brunswick, munit désormais les chercheurs d'une base de données détaillée pouvant servir à tout un éventail de disciplines. Parmi les autres applications possibles, les données pourraient être intégrées (et l'ont déjà été dans certains cas) dans des cartes d'aménagement régional, de détermination du potentiel de risque et de modélisation de l'hydrologie des sols forestiers.

Introduction and Previous Work

The contribution of surficial geology mapping to mineral exploration has a long and well documented history (Hawkes and Webb 1962; Coker and DiLabio 1989). In New Brunswick, information obtained from surficial mapping and till geochemistry studies has been used increasingly since the early 1980s to support mineral exploration activities (e.g. Fyffe and Pronk 1983). Surficial mapping in the province remains focused on mineral exploration targets, but data gathered during exploration also have been applied to other disciplines. Surficial information, for instance, was used to assess soil properties (Groenewoud and Ruitenberg 1982) and to investigate unconsolidated aquifers and recharge areas (Violette and Bray 1991).

Detailed surficial mapping and till geochemistry surveying has now been completed for large, continuous areas of the province. The resulting comprehensive database of soil parent material properties and site characteristics has a range of potential applications beyond mineral exploration (Pronk 1991), including the compilation of regional planning maps.

One recent example of surficial data being used for non-exploration purposes took place in southeastern New Brunswick within the Caledonian Highlands physiographic area (*after* Rampton et al. 1984). Surficial mapping was conducted over exploration targets on NTS 21 H/6, 11 to 14; 21 I/3 and 4; 21 G/9; and parts of 21 H/10 and 15 (Fig. 1). The survey area overlapped ground delineated for forestry research within the 420 000 ha Fundy Model Forest, which encompasses Fundy National Park and adjacent districts. Some of the preliminary surficial information (Munn et al. 1996) was incorporated into a regional forest soils map for New Brunswick (Colpitts et al. 1995). Although the map is the first such compilation of its kind for the province, it displays an inconsistent pattern of on-the-ground detail, as its authors selectively extrapolated some surficial information but did not include other data.

Surficial mapping of the Caledonian Highlands continued until the late 1990s (Allaby 2000) and was followed by additional laboratory and compilation activities in 2002 and 2003. The survey has since become a pilot project for the creation of more complex surficial mapping units that incorporate a wider range of field and laboratory data. The present report summarizes this pilot project and outlines its potential application to regional planning across the province.

Data Collection and Methodology

Regional till geochemical surveys are conducted widely and use a standardized methodology that readily facilitates the transfer of data to other applications. Researchers excavate soil pits on a regular 2 km grid and collect samples from the C-horizon basal till and B-horizon. Roadcuts are the most preferred sample locations, as they offer a broader stratigraphic and landscape context and

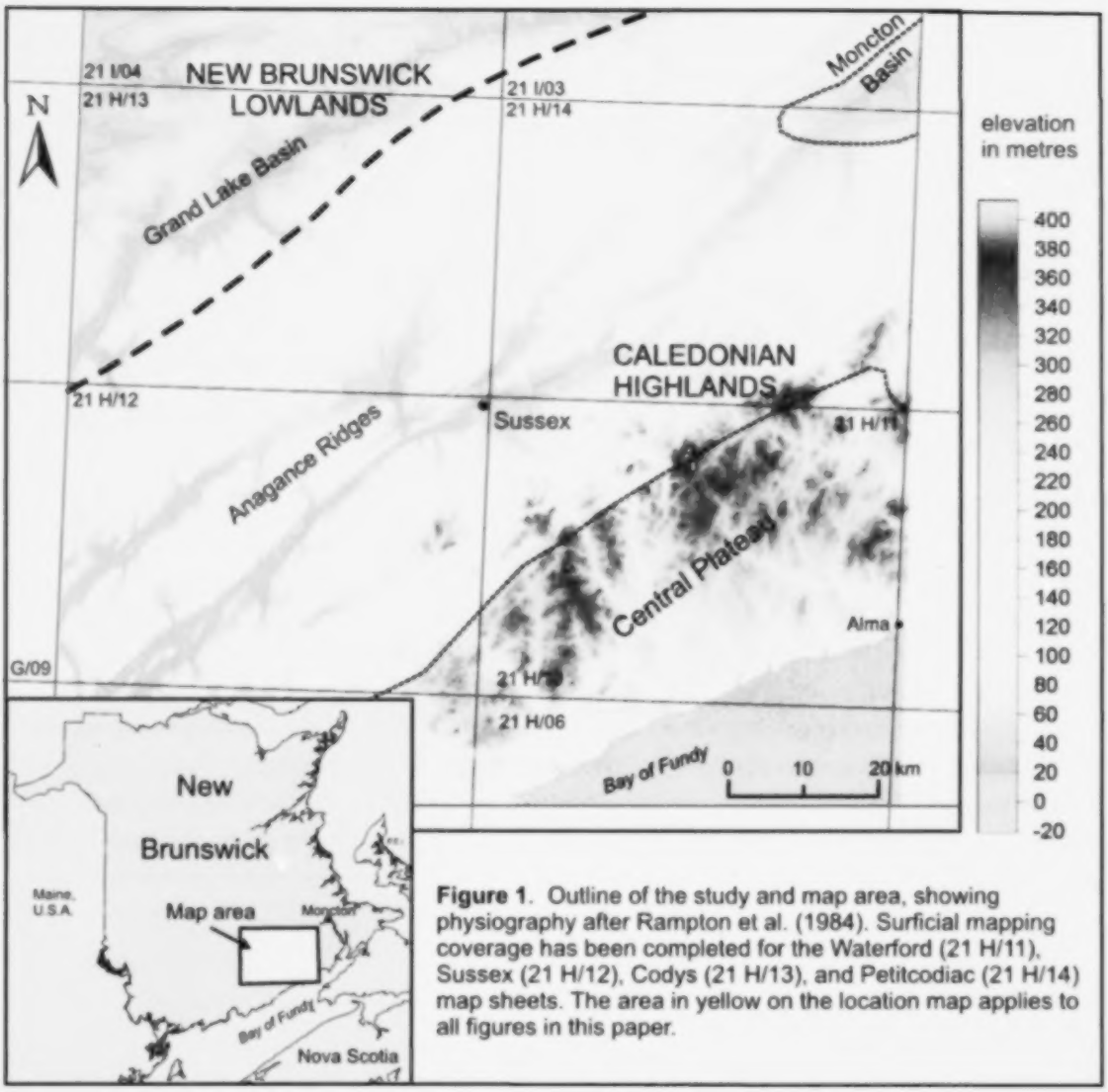
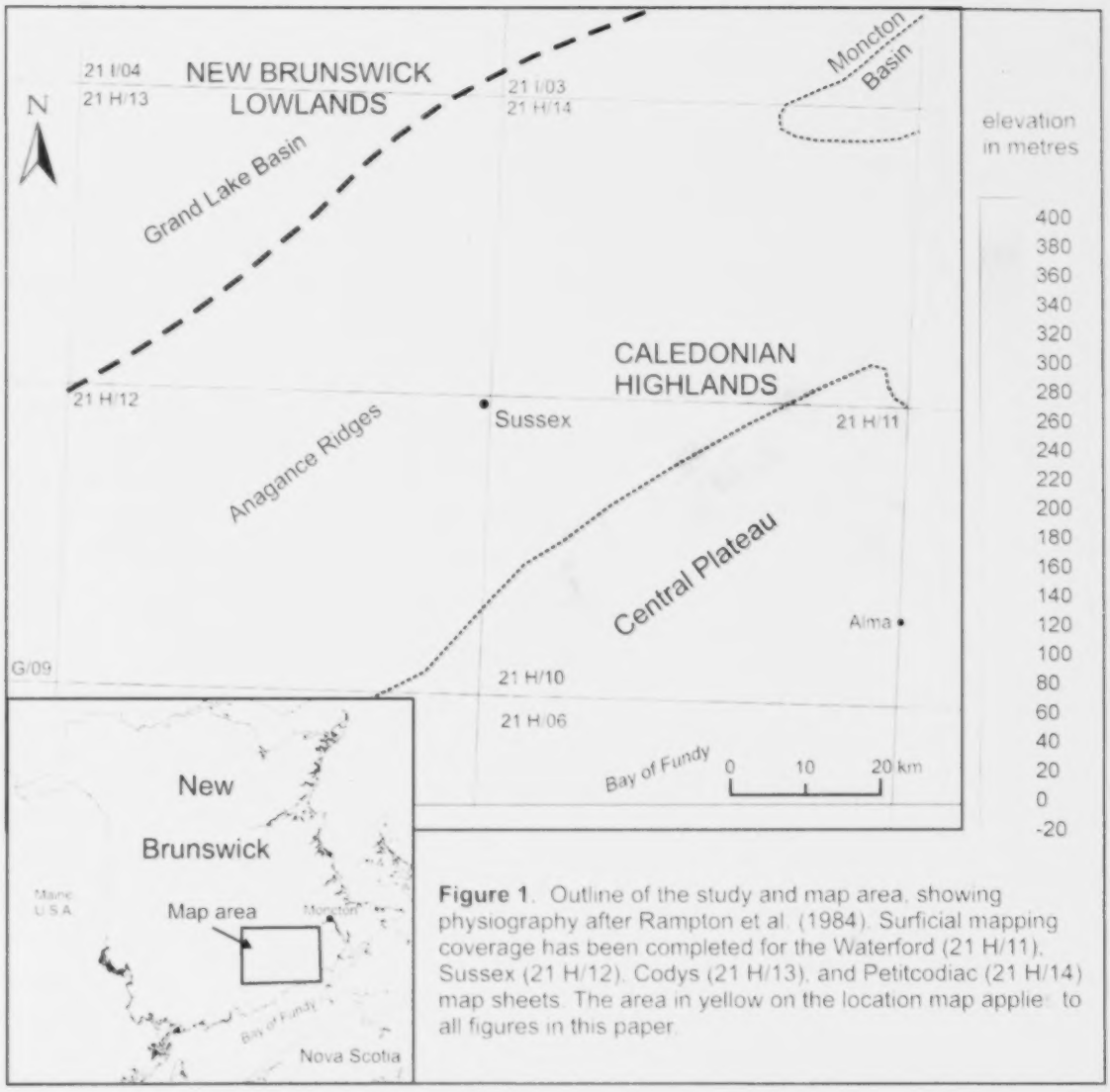


Figure 1. Outline of the study and map area, showing physiography after Rampton et al. (1984). Surficial mapping coverage has been completed for the Waterford (21 H/11), Sussex (21 H/12), Codys (21 H/13), and Petitcodiac (21 H/14) map sheets. The area in yellow on the location map applies to all figures in this paper.

thus allow for a more complete site description. Site reports record features such as slope steepness and exposure, soil texture, coarse fragments in soil, compactness, surface stoniness, depth to root-constricting layers, drainage, soil horizon thickness, and soil colours. Site descriptions also include a vegetation inventory of the overstory and understory species.

After sampling, researchers perform a lithological analysis of the clast component of the parent material, conduct a textural analysis, and test the sample for a large suite of geochemical parameters. Geochemical analyses are carried out primarily for elements and compounds relevant to mineral exploration, but in some regions the samples also are tested for plant nutrients. The information is assembled into digital databases, together with the associated B-horizon and vegetation information.



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Pronk (1997) compiled the preliminary surficial geology map for the Waterford area (NTS 21 H/11 on Fig. 1), using map units based on basic landform and clast lithology data. When the methodology was applied to other parts of the Caledonian Highlands, however, it became evident that these basic data yielded only some of the information needed to produce a reliable, practical map containing a full description for all units. It was decided instead to devise a procedure that would integrate a greater complexity of textural and lithological information into the existing landform data.

Landform Data

The Caledonian Highlands physiographic region adjoins the New Brunswick Lowlands region and contains several subregions including the Central Plateau, Anagance Ridges, and Moncton Basin (Fig. 1). Boundaries between regions and subregions in the study area proved to be a useful approximation for many of the boundaries drawn between divisional units on the surficial geology map.

The most prevalent type of landform in the Caledonian Highlands comprises fairly thin till units that generally reflect local bedrock geology. The till material was glacially transported and has undergone a moderate degree of mixing. Till composition has been influenced by the bedrock type, ice dynamics, and topography. Many regional valleys contain deposits of glaciofluvial and fluvial origin. These sand and gravel deposits typically are coarser grained, and have a higher permeability, than tills. Such characteristics strongly influence the entire hydrology of a given site, especially its permeability, recharge ability, and drainage features.

Areas with slopes of greater than 25% are prone to mass-wasting processes, have exposed bedrock, and usually are covered by colluvium. These areas initially were mapped solely with the aid of aerial photographs. Map images now are produced in part by the inclusion of digital terrain models obtained from the United States Geological Survey (USGS–DTM 2003) and adapted with Surfer® software. Such maps clearly highlight the steeper slopes and valleys along the Bay of Fundy coastline, showing many small landslide scars (Fig. 2). Landscape of this type is considered marginal to poor in terms of its usefulness to agriculture and forestry.

Lithological and Textural Data

Pebble lithology data for each sample site were obtained by determining the lithology of between 50 and 100 gravel-sized clasts larger than 2 cm in diameter. Map units initially were produced by outlining sites that were dominated by one lithological type: that is, those containing more than 50% volcanic rocks, more than 50% plutonic rocks or more than 80% sedimentary rocks (Fig. 3). Subsequent, more refined determinations were made using various combinations and proportions of clast lithologies.

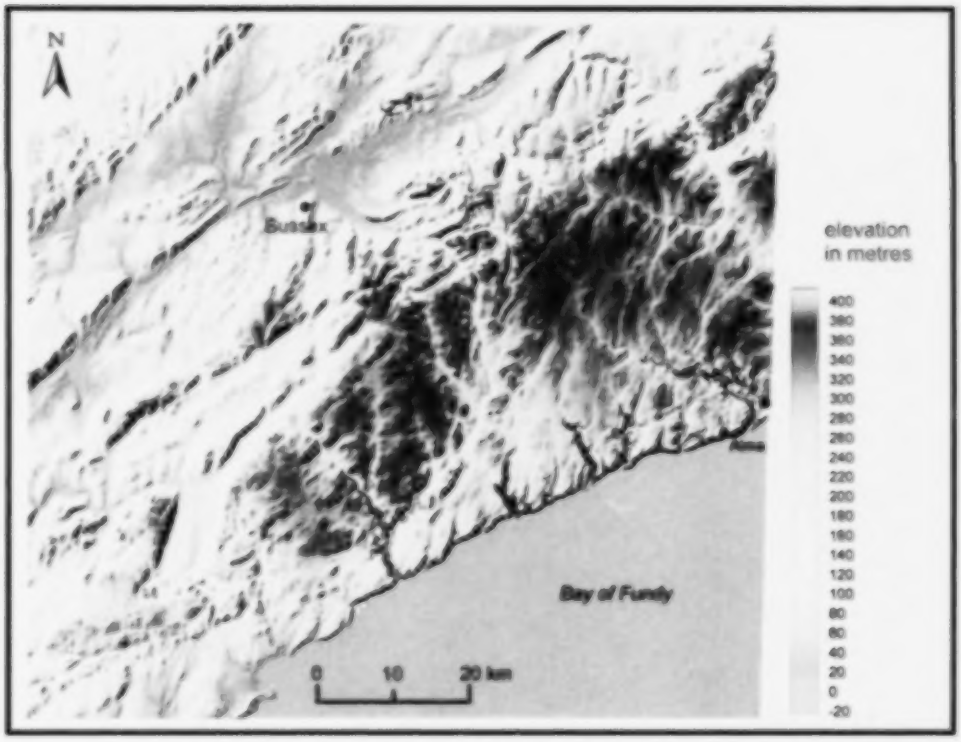


Figure 2. Digital terrain model image of study area, showing the Bay of Fundy coastline adjacent to the Caledonia Highlands. Slopes steeper than 25% are marked in red.

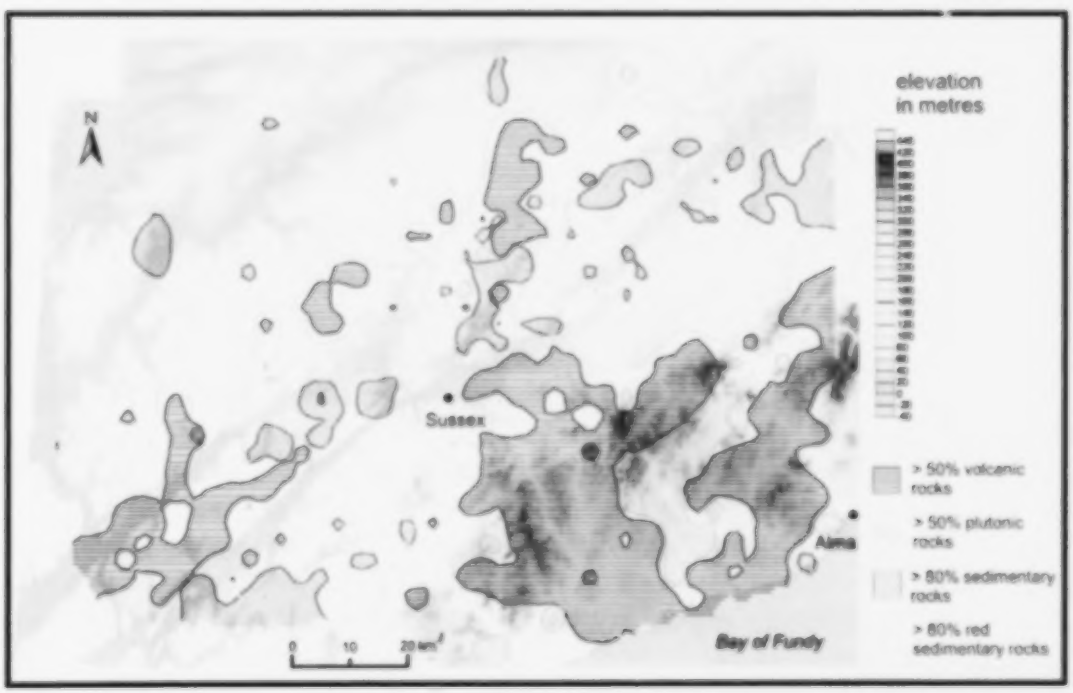


Figure 3. Dominant till lithologies used to delineate soil parent material units.

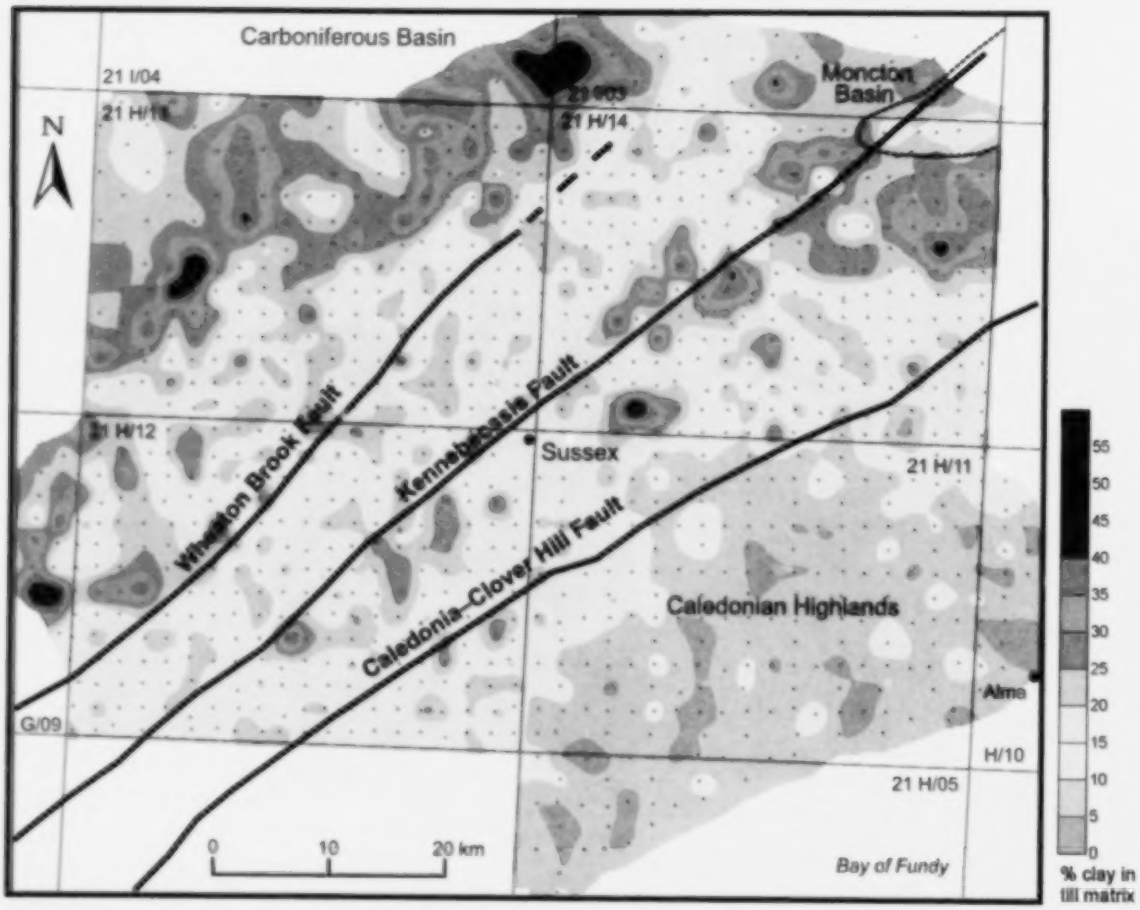


Figure 4. Clay content of till matrix in the study area. Note the low clay content over the Central Plateau of the Caledonian Highlands (*see* Fig. 1), high clay content over the Carboniferous Basin in the northwest, and high clay content over sedimentary rocks of the Cumberland Group in northeast.

Texture of the till matrix became an additional parameter to further subdivide and modify the units. Although texture of the soil parent material was identified in the field, texture of the till matrix — that is, the sand–silt–clay ratio — was determined in the laboratory using a modified hydrometer methodology (Bouyoucos 1962). Clay and sand percentages in the till matrix were plotted for the entire study area to identify large-scale patterns.

Very low clay percentages (<10%) are found over the Central Plateau of the Caledonian Highlands (Fig. 1, 4). Higher clay percentages (>20%) occur over the New Brunswick Lowlands, which are underlain by Carboniferous sandstone and siltstone (Fig. 1, 4). The intervening terrain covers the Anagance Ridges and northern edge of the Central Plateau and has a more heterogeneous composition of 10 to 25% clay. Nonetheless, minor local fluctuations in texture can be observed. The northeastern portion of the study area near the Moncton Basin, for example, is underlain by Cumberland Group sedimentary rocks and has a high clay content, similar to that of till overlying the New Brunswick Lowlands (Fig. 4).

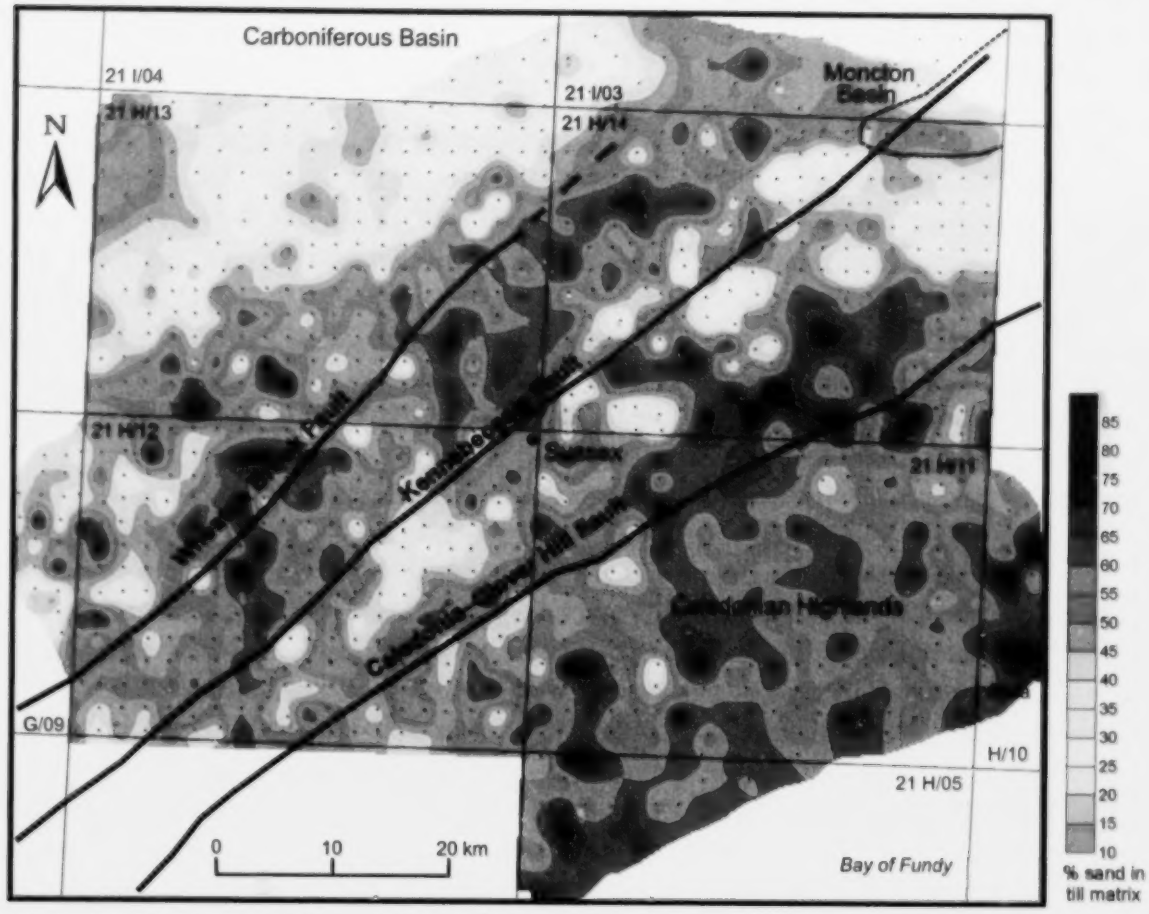
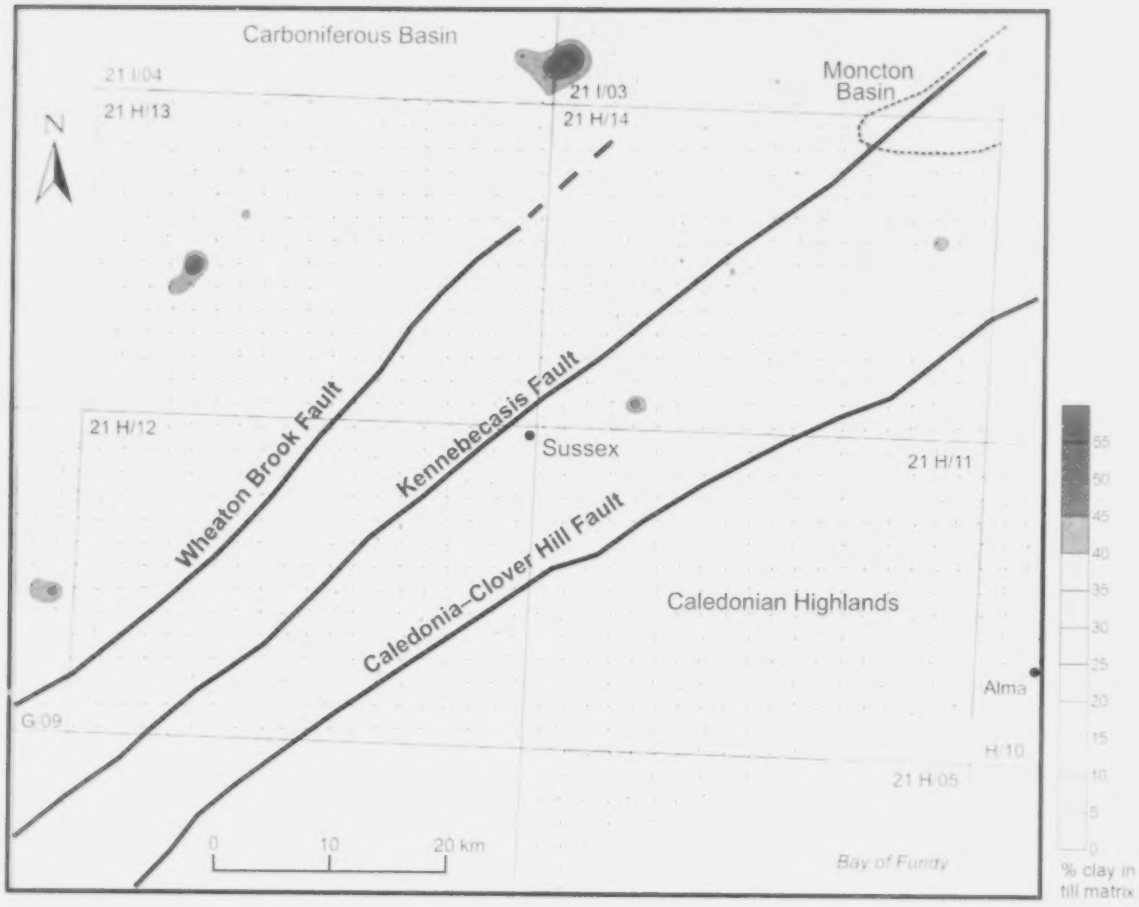


Figure 5. Sand content of till matrix in the study area. Note the relatively low sand content in the Carboniferous Basin area and higher sand content over the Caledonian Highlands.

Plots of sand percentages in the till matrix exhibit almost a mirror image of the clay content plots, although the sand plot results are less well defined (Fig. 5). The sand content is high (>40%) over the entire Caledonian Highlands area and consistently high (>50%) over the Central Plateau. It is lowest (<40%) in parts of the New Brunswick Lowlands to the northwest and in regions underlain by Cumberland Group sedimentary rocks to the northeast. The soil patterns of both clay and sand generally follow geological divisions but are modified locally by glacial dispersion and mixing (Fig. 4, 5).

All lithological and textural data were manipulated with Surfer® software. Bedrock, physiographic boundaries, topographical features, and differences in matrix colour also were used as variables to produce a more comprehensive data set. Each site on the full-scale map records soil compactness, texture, depth to contrasting layer, drainage, and surface stoniness. Additional parameters have been entered in the final database and will be made available for the entire study area.



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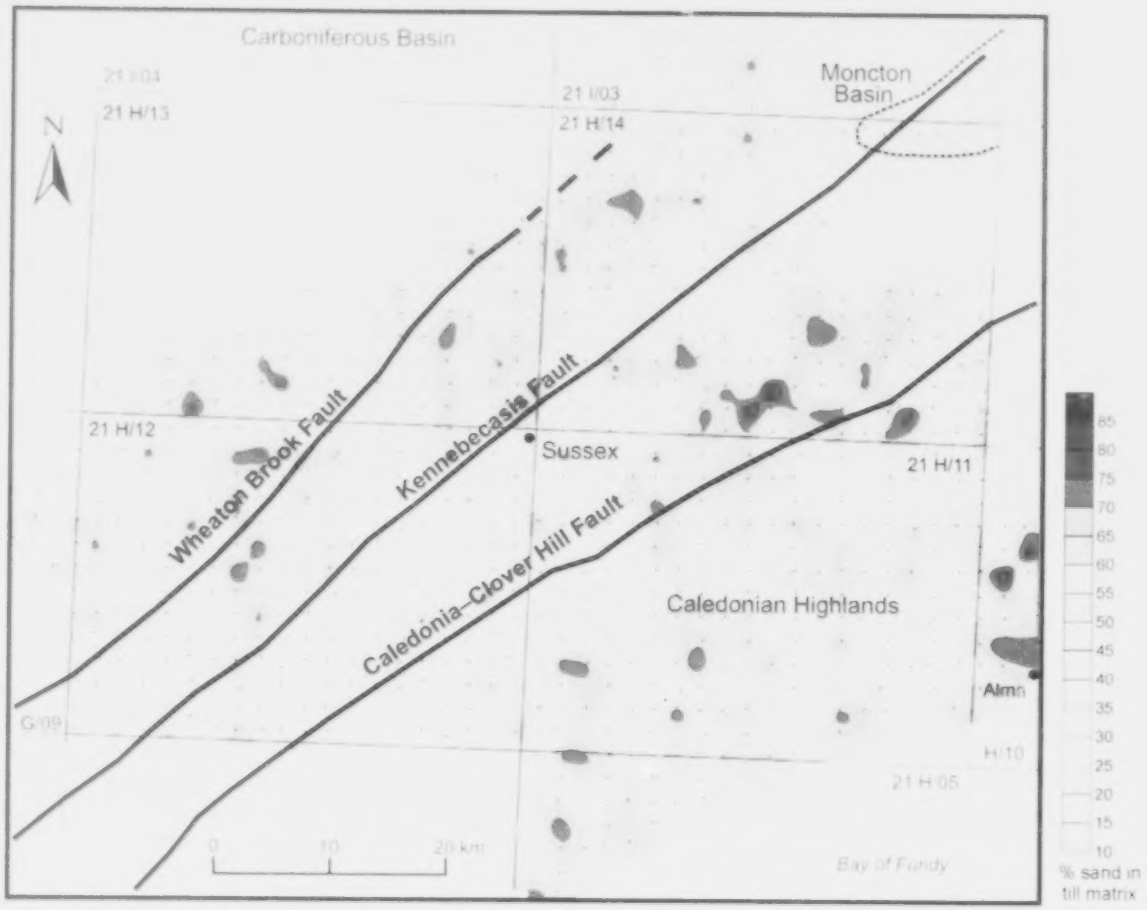

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DISCUSSION

The New Brunswick landscape has many traditional uses, ranging from forestry and mining to agriculture and recreation. We seek to preserve landscapes and their associated ecosystems, partly for their inherent, aesthetic value, but also because of their crucial role in natural resource development, air and water quality, and wildlife habitat. These different and sometimes conflicting demands on the landscape all have an effect on ecosystems. As societal and industrial needs shift over time, the knowledge of landscape processes becomes increasingly significant, as does the production of reliable, comprehensive land use planning maps.

Vegetation and soil conditions can change rapidly by geological standards, commonly doing so as a result of alterations in land use. Conversely, the physical and chemical properties of soil parent materials — features that form the core of our surficial databases — usually remain constant for decades and possibly centuries. The land use planning maps we currently are producing in co-operation with regional planners, foresters, and others have focused on these longer term physical properties. The maps provide important information for regional planning committees needing to assess such factors as forest productivity, vulnerability of recharge areas, and susceptibility of terrain to slope failure. Advanced computer technology and integrated data management together will facilitate the application of surficial mapping and till geochemistry data to these and other disciplines beyond mineral exploration.

This paper has concentrated on the rural and forested landscape as opposed to the urban environment. Physical landscape parameters are no less significant in urban areas but are more altered. Issues such as rainwater infiltration and run-off, urban soil pollution, and landfill site location are increasingly better understood and accommodated in urban planning. Even so, regional planners working in urban areas could benefit from incorporating these new surficial databases into their work.

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THE MALISEET SOUTH ZN MASSIVE-SULPHIDE OCCURRENCE, SOUTHWESTERN BATHURST MINING CAMP, NEW BRUNSWICK

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WALKER, J.A. 2004. The Maliseet South Zn massive-sulphide occurrence, southwestern Bathurst Mining Camp, New Brunswick. *In* Geological Investigations in New Brunswick for 2003. *Edited by* Gwen L. Martin. New Brunswick Department of Natural Resources; Minerals, policy and Planning Division, Mineral Resource Report 2004-4, pp. 105–130.

The Late Silurian–Early Devonian Goodwin Lake Gabbro has been explored for magmatic Cu–Ni mineralization with moderate success since the early 1960s. Recent work by Mountain Lake Resources resulted in the discovery of semi-massive to massive, high-grade (up to 17 wt % Zn), VMS-style mineralization on the margin of the Goodwin Lake Gabbro. Regional mapping suggests that the gabbro intruded along the contact between the Knights Brook Formation (Miramichi Group), and felsic volcanic and related volcaniclastic rocks of the Mount Brittain Formation (California Lake Group). Petrographic, lithogeochemical, and $\delta^{34}S$ work suggest that the Zn-sulphide mineralization is probably the remnant of a Middle Ordovician VMS deposit originally hosted by the Mount Brittain Formation. Moreover, magmatic Cu–Ni occurrences hosted by the Goodwin Lake Gabbro also likely owe their existence to the Zn-rich VMS body. Recognition of the Maliseet South Zn occurrence as VMS-type mineralization provides another example of a volcanic massive-sulphide deposit in the California Lake Group.

On a exploré, avec un certain succès, le gabbro du Silurien tardif au Dévonien précoce du lac Goodwin en vue d'y repérer une minéralisation magmatique de Cu–Ni depuis le début des années 60. Des travaux récents de la Mountain Lake Resources ont abouti à la découverte d'une minéralisation de SMV semi-massive à massive à forte teneur (jusqu'à 17 % de Zn) sur le bord du gabbro du lac Goodwin. Des travaux de cartographie de la région permettent de supposer que le gabbro s'est introduit le long de la zone de contact entre la Formation de Knights Brook du groupe de Miramichi et les roches volcanofelsiques et volcanoclastiques connexes de la Formation de Mount Brittain du groupe du lac California. Des travaux pétrographiques, lithogéochimiques et au $\delta^{34}S$ permettent de supposer que la minéralisation de sulfures de Zn constitue probablement un vestige d'un gîte de SMV de l'Ordovicien moyen initialement inclus dans la Formation de Mount Brittain. Les venues magmatiques de Cu–Ni incluses dans le gabbro du lac Goodwin doivent par ailleurs probablement leur existence à la masse de SMV riche en zinc. Le fait qu'on reconnaisse le venue de Zn de Maliseet South en tant que minéralisation de SMV procure un autre exemple de gîte de sulfures massifs volcanogènes à l'intérieur du groupe du lac California.

INTRODUCTION

The Maliseet South Zn occurrence, New Brunswick Department of Natural Resources unique reference number (URN) 023, was discovered in 1997 by Mountain Lake Resources during exploration for magmatic Cu–Ni mineralization in the Goodwin Lake Gabbro (Mersereau 1998a, b). The occurrence is situated in the southwestern part of the Bathurst Mining Camp (BMC), 68 km southwest of the City of Bathurst, 25 km west of the abandoned Heath Steele mine site, and 3 km northwest of Goodwin Lake (Fig. 1, 2). The present study documents the style of mineralization and alteration associated with this atypical occurrence, and proposes a genetic model that might facilitate the search for additional deposits.

PREVIOUS WORK

Previous work near the Maliseet South Zn occurrence (NTS 21 O/8) focused on exploration for magmatic Cu–Ni mineralization in the Goodwin Lake Gabbro at Maliseet South (URN 022). Four occurrences of this mineralization type have been reported from the Goodwin Lake Gabbro (Fig. 2): Maliseet North (URN 021), Maliseet South (URN 022), Maliseet South Zn (URN 023), and Maliseet East (URN 024). Pertinent assessment reports concerning the occurrences are summarized below.

In 1960 and 1961 Noranda Exploration Company Ltd. conducted geophysical and soil geochemical surveys, and drilled holes 1 to 6 and 10 (Noranda Explorations 1962; Sawyer 1963a, b, 1964). Their work concentrated on Cu–Ni-sulphide mineralization at the Maliseet North and East zones (Fig. 2). In 1971 MicMac Mines Ltd. drilled holes M-71, -4, -5, and -5B, which focused on Cu–Ni mineralization at the Maliseet North zone (McAllister 1971).

Granges Exploration Ltd. carried out the next reported work in the area, drilling hole R-87-38 (O'Donnell 1987). In 1990 the company noted interesting Zn and Pb mineralization in drillhole R-66 about 1 km southeast of the present study area (Fig. 2; Morris 1991) and implemented a second phase of drilling in the same location. These drillholes intersected quartz-chlorite-sericite schist assigned to the Mount Brittain Formation (Fig. 2). Intersections were reported that locally contained up to 40% sulphides; they consisted mainly of pyrite-pyrrhotite, but included trace amounts of sphalerite and galena (Morris 1991). Mersereau (1995a, b) summarized the soil geochemistry surveys and drill core recovery by Granges Exploration.

In 1997 and 1998 Mountain Lake Resources drilled 12 holes (ML-97-1 through -6; ML-98-7 through -12) to test for Cu–Ni mineralization near the Maliseet South (URN 022) occurrence (Mersereau 1998a–c). One of these drillholes, ML-97-2, intersected 15.9 m of semi-massive to massive Zn–Cu sulphide (Mersereau 1998b). Core from hole ML-97-2 is the subject of the present study.

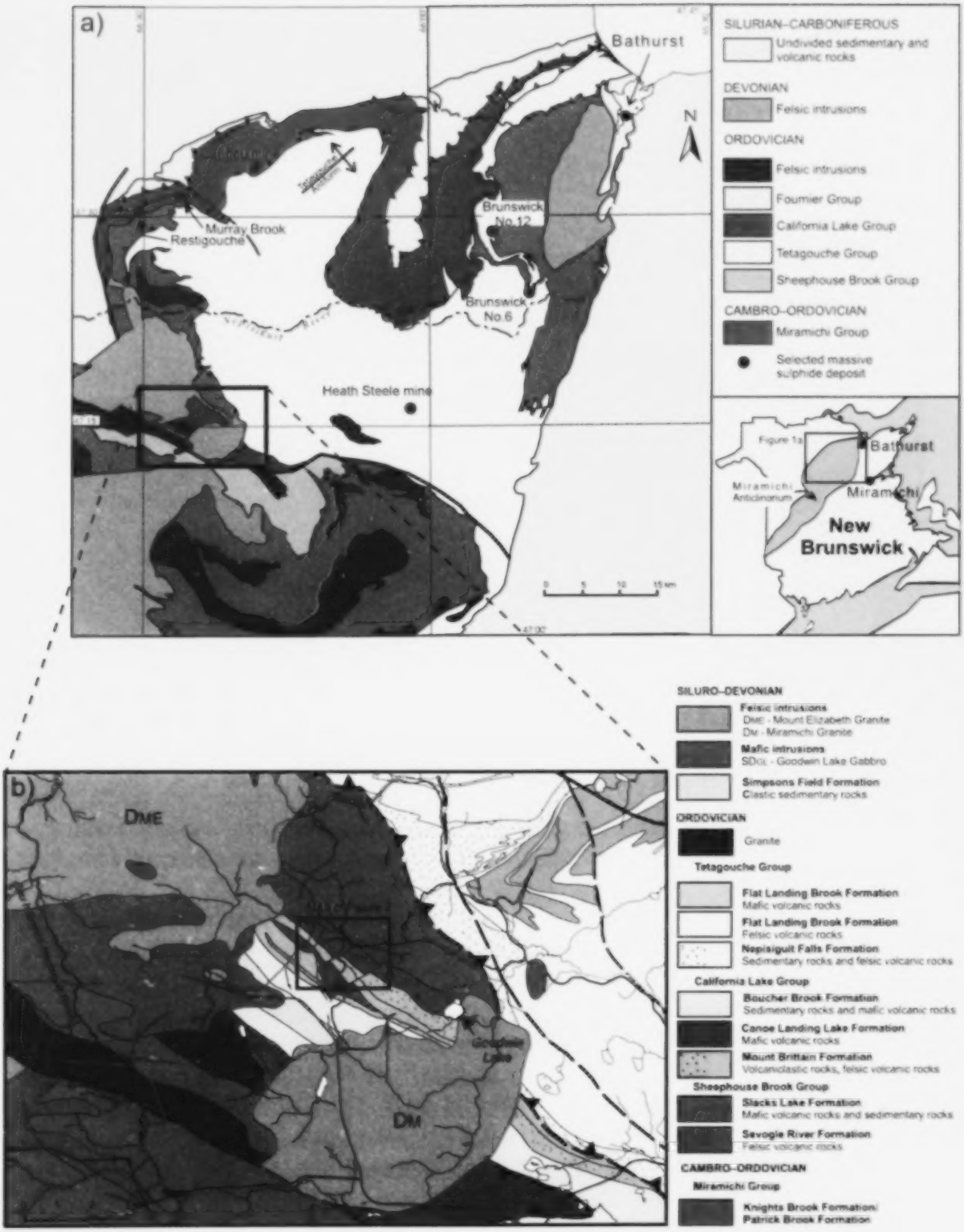
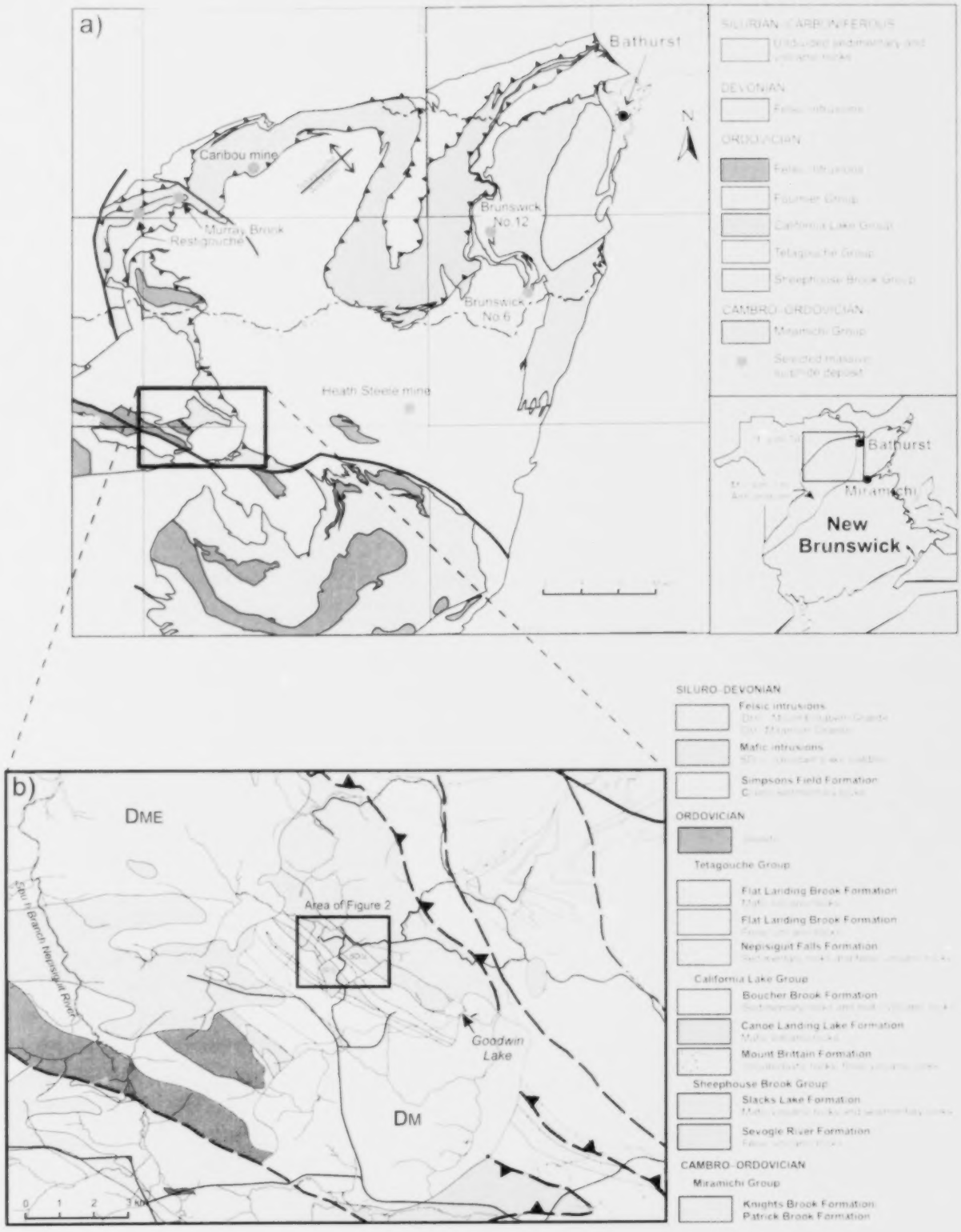


Figure 1. Major geological divisions of Bathurst Mining Camp, after van Staal et al. 2003. a) Regional view of Bathurst Mining Camp. b) Regional view of area surrounding Maliseet occurrences.



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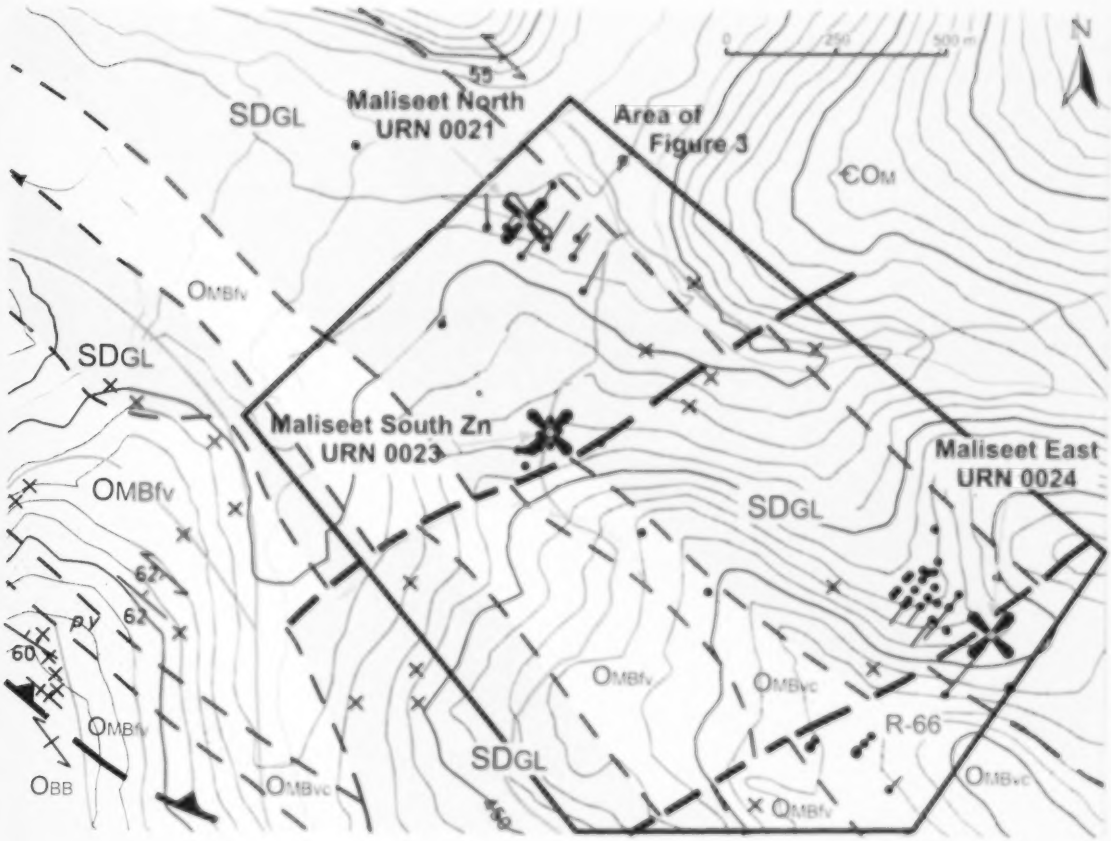
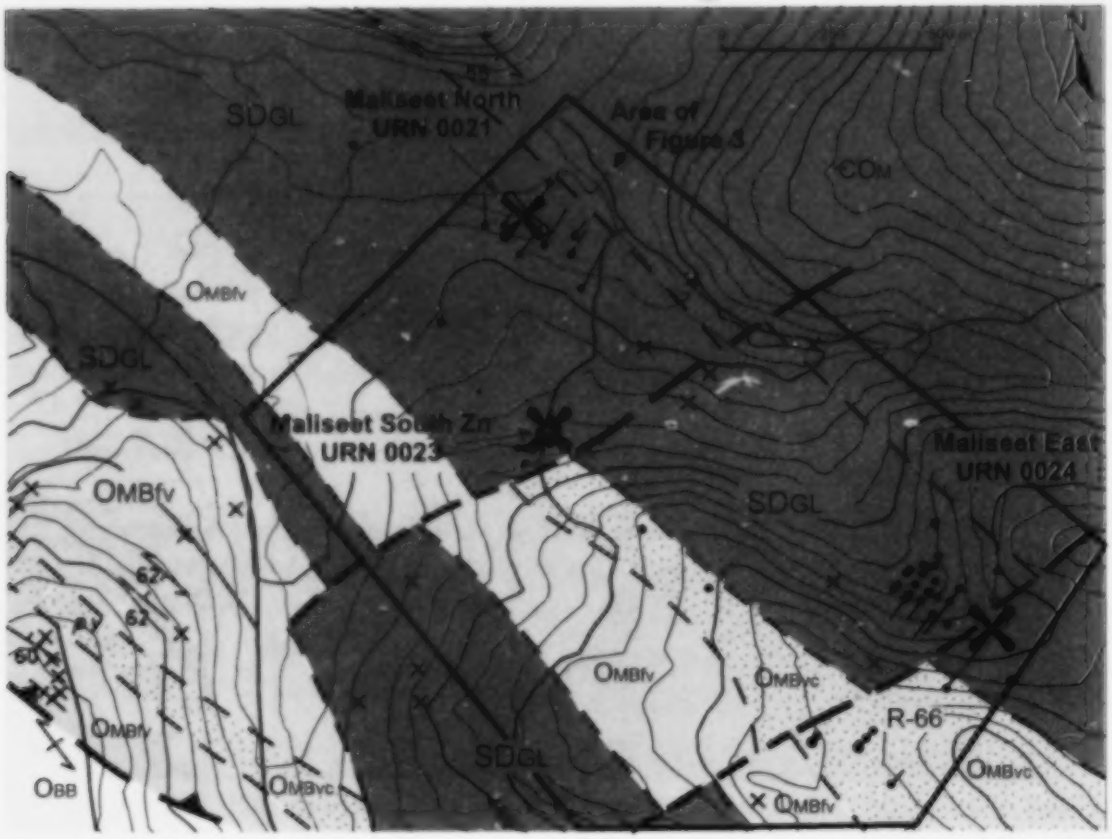


Figure 2. Local geology of the area surrounding the Maliseet mineral occurrences. Black circles mark the drillhole positions. Black crosses show the location of Maliseet North, Maliseet South Zn, and Maliseet East occurrences. (Maliseet South lies immediately west of Maliseet South Zn.) €OM = Miramichi Group; OBB = Boucher Brook Formation; OMBfv = Mount Brittain Formation - felsic volcanic rocks; OMBvc = Mount Brittain Formation - volcaniclastic rocks; SDGL = Goodwin Lake Gabbro. See Figure 1b for map location. Base map and geology are compiled from Wilson (1996) and van Staal et al. (2003); the contour interval is 10 m.

Regional Geology

The southwestern portion of the Bathurst Mining Camp contains a mixed sequence of volcano-sedimentary and bimodal volcanic rocks and related intrusions that date from the Cambro–Ordovician through to the Early Devonian. Recent 1:20 000-scale mapping in the area shows a complex geology (Wilson 1993). The stratigraphic succession in ascending order comprises 1) siliciclastic rocks of the Cambro–Ordovician Knights Brook Formation, 2) felsic volcanic rocks including interlayered volcaniclastic rocks of the Middle Ordovician Mount Brittain Formation, 3) mafic volcanic and related sedimentary rocks of the Boucher Brook Formation, and 4) Silurian clastic sedimentary rocks of the Simpsons Field Formation (van Staal et al. 2003). Van Staal et al. (2003) and references contained therein provide additional information about stratigraphy and structure of the BMC. This tectonostratigraphic succession subsequently was intruded by the Goodwin Lake Gabbro and later by granitic plutons of the Mount Elizabeth Plutonic Suite.



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Knights Brook Formation

The Knights Brook Formation represents the upper part of the Cambro–Ordovician Miramichi Group in the southwestern part of the BMC (Fig. 1–3). The formation consists of clastic sedimentary rocks that include greyish-green quartzose sandstone, and light green, dark grey, and black shale. These rocks lie northeast of the Maliseet mineral occurrences and were not intersected in the drill core. Throughout the BMC, the Knights Brook Formation generally is overlain by dark grey wacke and shale of the Patrick Formation, although this wacke facies has not been recognized in the immediate vicinity of Goodwin Lake.

Mount Brittain Formation

Rocks situated west and south of the Maliseet South Zn occurrence represent the upper part of the Early Paleozoic stratigraphic sequence in the southwestern BMC. These polydeformed felsic volcanic and related volcaniclastic rocks have been assigned to the Mount Brittain Formation of the California Lake Group (van Staal et al. 2003).

The type area of the Mount Brittain Formation occurs in the northern part of the BMC between the Murray Brook and Restigouche volcanic massive-sulphide (VMS) deposits (Fig. 1a). In this area, the Mount Brittain Formation comprises a lower volcaniclastic unit that gradationally overlies wacke and shale of the Patrick Brook Formation, and an upper felsic volcanic unit formed of crystal- and crystal-lithic tuffs. U–Pb dating of zircons from a felsic tuff have yielded an age of 468 ± 2 Ma for the Mount Brittain Formation (Gower and McCutcheon 1997).

Boucher Brook and Simpsons Field Formations

The Mount Brittain Formation is conformably overlain by mafic volcanic rocks and fine-grained clastic rocks of the Boucher Brook Formation (Fig. 1, 2). The Boucher Brook in turn is unconformably overlain by clastic sedimentary rocks of the Silurian Simpsons Field Formation. Neither the Boucher Brook nor the Simpsons Field formation host mineralization.

Goodwin Lake Gabbro

The foregoing succession was intruded by the Goodwin Lake Gabbro, which hosts both magmatic Cu–Ni-sulphide occurrences and a Zn–Pb-sulphide occurrence. The intrusion consists of two subparallel gabbro sills that strike northwest, dip steeply southwest, and are approximately 6.5 km long (Fig. 2). In the northwest they abut the Mount Elizabeth Granite, whereas to the southeast they either pinch out or are truncated by the Miramichi Granite (Whalen 1993). Several phases have been recognized within the sills including gabbro, gabbronorite, norite, peridotite, and locally troctolite (Paktunc 1988; Mersereau 1998b). McNutt (1962), Mercer (1988), and Paktunc (1988) provide additional information on the gabbro and its related magmatic Cu–Ni mineralization.

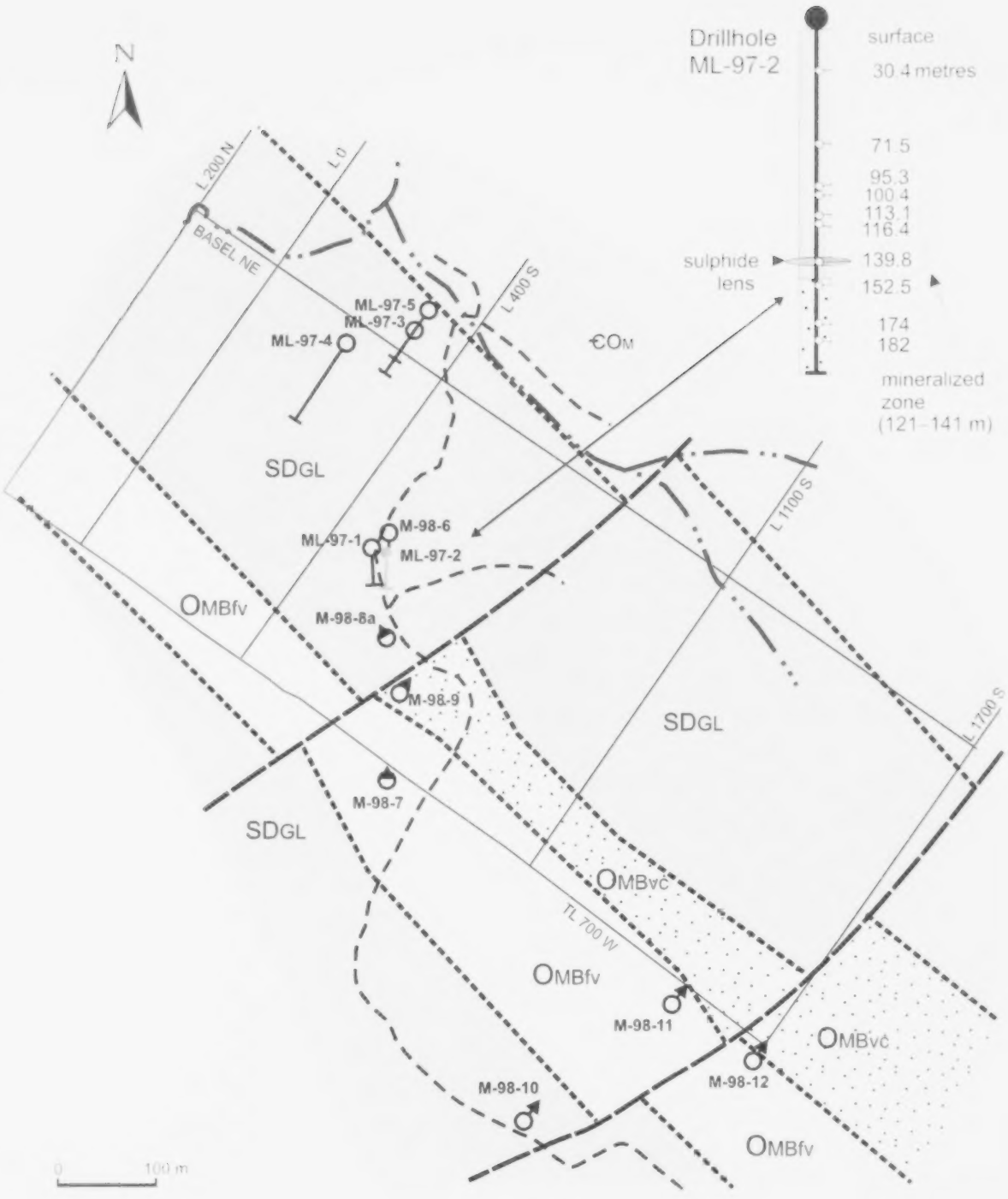
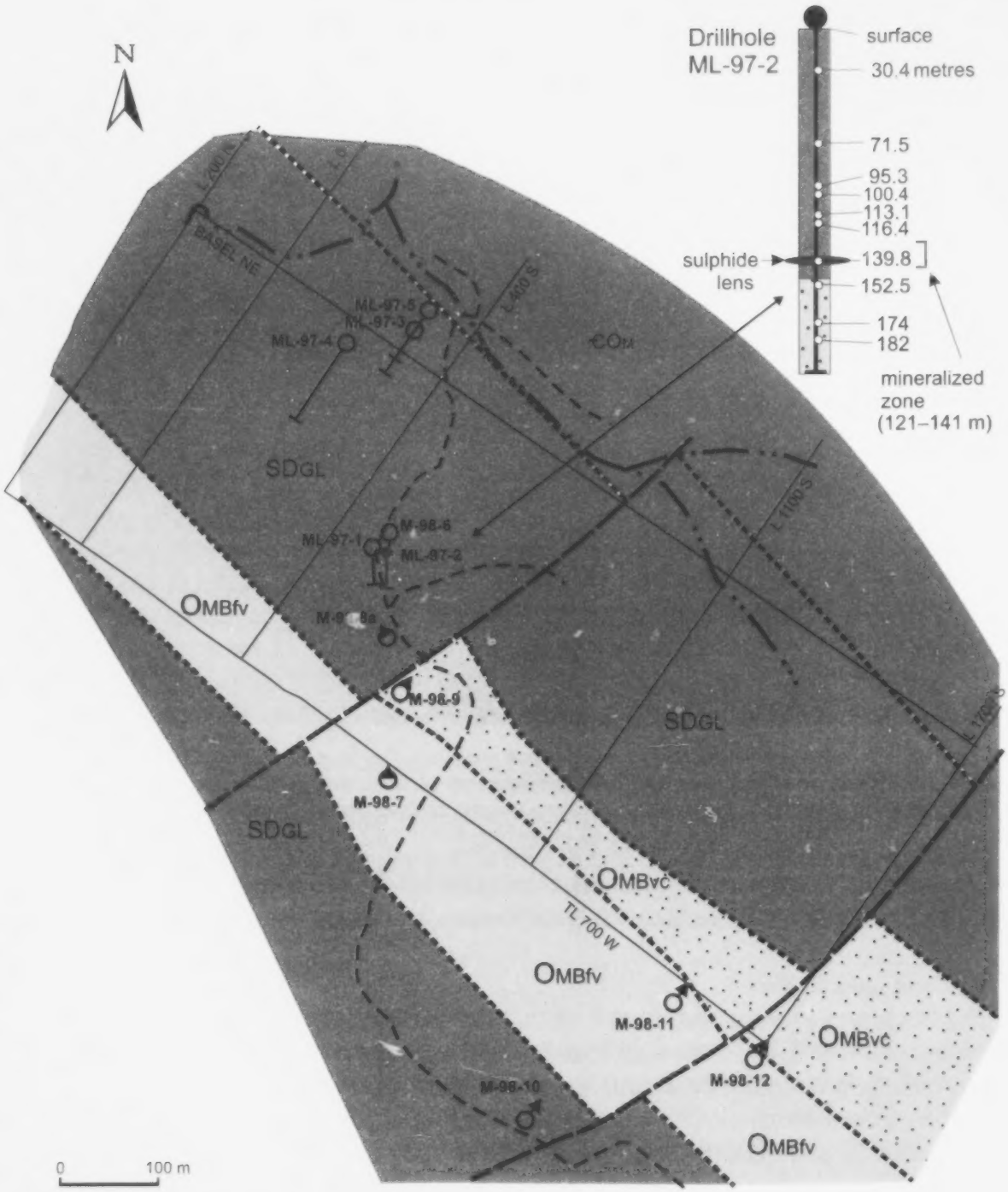


Figure 3. Detailed geology near the Maliseet South Zn occurrence, indicating position of the Mountain Lake Resources drillholes and grid (Mersereau 1998a–c). Inset of drillhole ML-97-2 shows simplified geology and depth locations of samples in Table 1. Location of this figure is marked on Figure 2. €OM = Miramichi Group, OBB = Boucher Brook Formation, OMBfv = Mount Brittain Formation - felsic volcanic rocks, OMBvc = Mount Brittain Formation - volcaniclastic rocks, SDGL = Goodwin Lake Gabbro.



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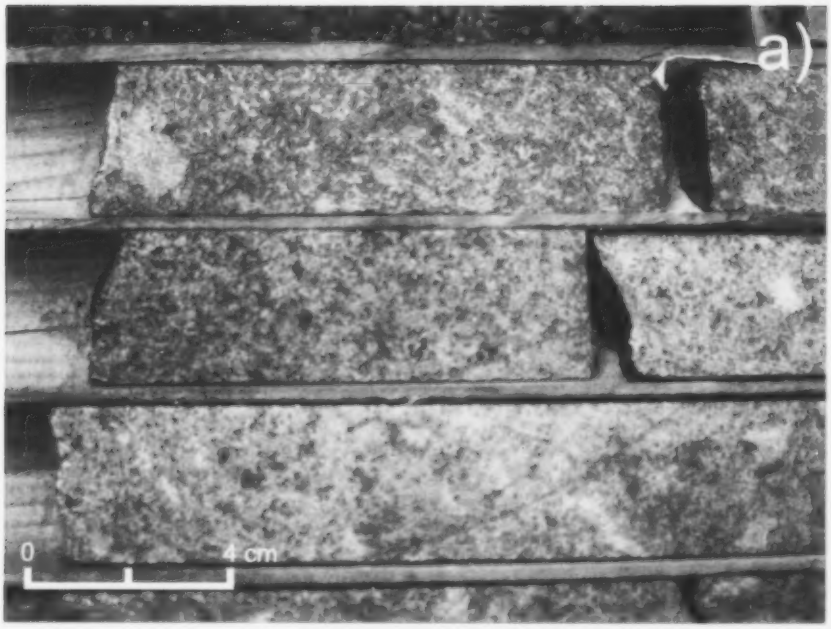
The eastern sill intrudes along the contact between the Knights Brook and Mount Brittain formations and varies in thickness from 500 to 900 m. The western sill reaches a maximum thickness of only 600 m and pinches out along strike to the northwest and southeast (Fig. 2, 3). The Goodwin Lake Gabbro has not been dated directly but is interpreted as an older mafic phase of the Mount Elizabeth Granite, which yielded a U–Pb zircon age of 417 ± 2 Ma (Bevier and Whalen 1990).

Several gabbroic phases were recognized in drillhole ML-97-2 (Fig. 3, 4a, b). The gabbroic rocks are dominated by plagioclase and contain abundant pyroxene. In most sections, however, pyroxene is altered to amphibole that in turn is altered to biotite (Fig. 4c, d). White mica (sericite) is abundant in the interstices between feldspar crystals and also occurs locally as a product of feldspar alteration (Fig. 4c, d). Magnetite is the common opaque phase in the least-altered, non-sulphide-bearing intrusion (Fig. 4d).

The presence of biotite in this intrusion suggests that water activity increased as crystallization progressed. This phenomenon could be explained by two mechanisms. First, normal crystallization of a melt generally favours an increase in H_2O activity as crystallization increases. Second, water may be introduced by assimilation of water-rich host rocks or by mixing a more evolved, higher a_{H_2O}, magma. It is unclear which of these mechanisms is responsible for biotite in the Goodwin Lake intrusion.

Rocks at the bottom of drillhole ML-97-2 lie structurally below the Zn-sulphide zone and originally were assigned to the Nepisiguit Falls Formation of the Tetagouche Group (Wilson 1996). Subsequently they were reassigned to the Mount Brittain Formation of the California Lake Group (van Staal et al. 2003). These rocks are almost completely recrystallized but locally have fragmental textures (Fig. 5a). They consist of fine- to medium-grained feldspar grains, biotite (3–10 wt %), minor quartz (1 wt %), and local biotite (Fig. 5b, c). The feldspars are moderately to well rounded, variable in size, and generally contain inclusions (Fig. 5b, c). The differing grain sizes may represent primary coarse- and fine-grained beds or could reflect recrystallization of primary fine-grained layers to coarse-grained ones, and vice versa. The biotite crystals appear to overgrow feldspar and fill interstices, and are euhedral (Fig. 5c). They also display a preferred orientation, which suggests that they formed in a stress regime. Large crystals of feldspar locally are intergrown with magnetite and sulphides (Fig. 5b, c), a texture that implies rapid growth in an igneous environment.

The chemistry of these rocks (*see* LITHOGEOCHEMISTRY) implies a felsic affinity. The degree of recrystallization makes it difficult to determine if they initially were volcanic or volcaniclastic, but regional mapping suggests the latter origin is more likely. Sericite development is highly variable throughout the sedimentary intersection. Some sections appear unaltered, whereas others contain 20 to 30% sericite.



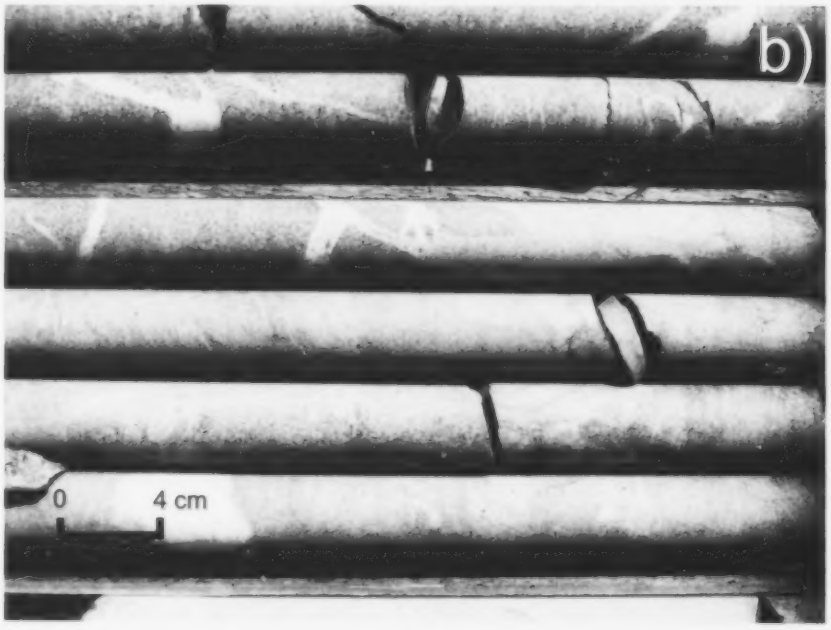
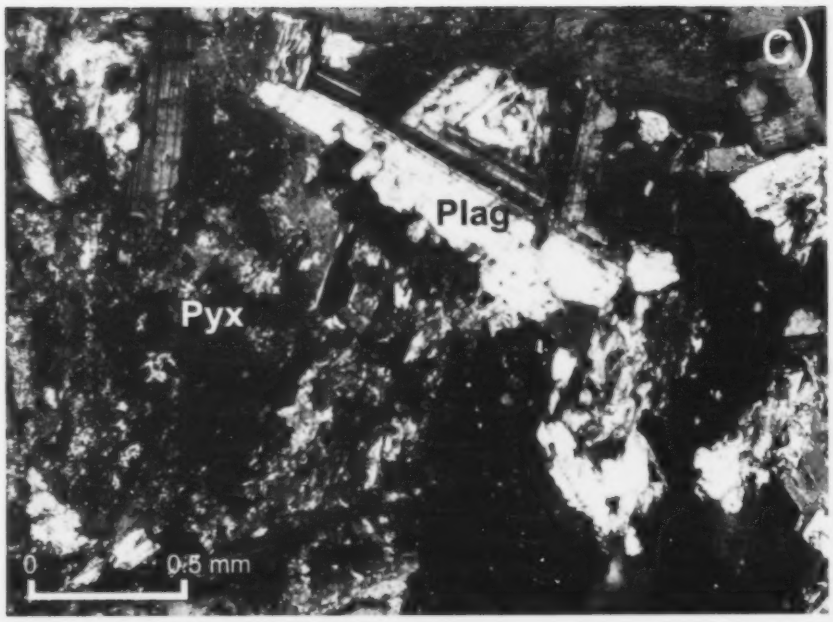


Figure 4. Goodwin Lake Gabbro at the Maliseet South Zn occurrence. a) Core from drillhole ML-97-2 shows the gabbro at approximately 110 m, uphole from the mineralized zone. The sample contains 1 to 2% patchy pyrrhotite. b) Same as Figure 4a, but shows contact between rocks of the Mount Brittain Formation and the Goodwin Lake Gabbro at about 145 m.



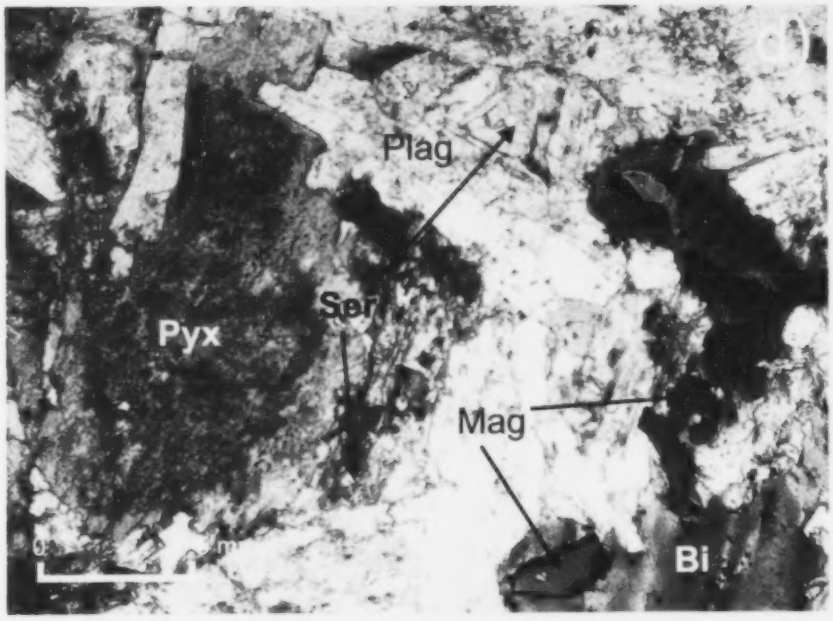


Figure 4 (cont'd). Goodwin Lake Gabbro at the Maliseet South Zn occurrence. c) Photomicrograph of gabbro showing plagioclase crystals and pyroxene under crossed nicols, from drillhole ML-97-2, sample ML-97-2-30.4. d) Same as Figure 4c, but with plane polarized light. Note the biotite and magnetite. Pyx = pyroxene, Plag = plagioclase, Mag = magnetite, Ser = sericite.

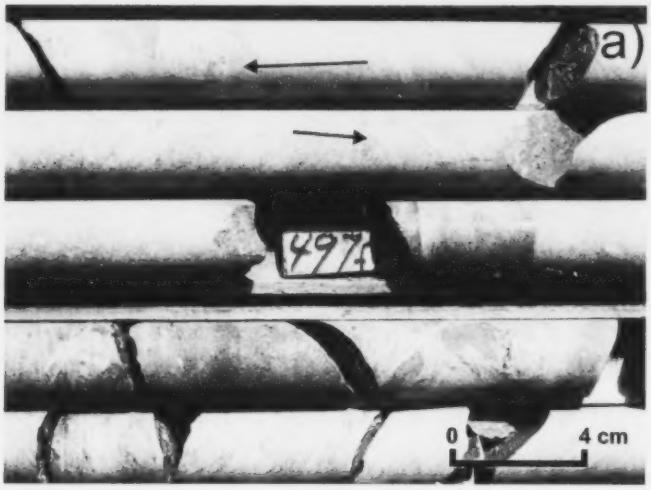


Figure 5a. Rocks of the Mount Brittain Formation at the Maliseet South Zn occurrence. Shows core from drillhole ML-97-2 at approximately 152 m. The arrows indicate fragmental texture in the rock.

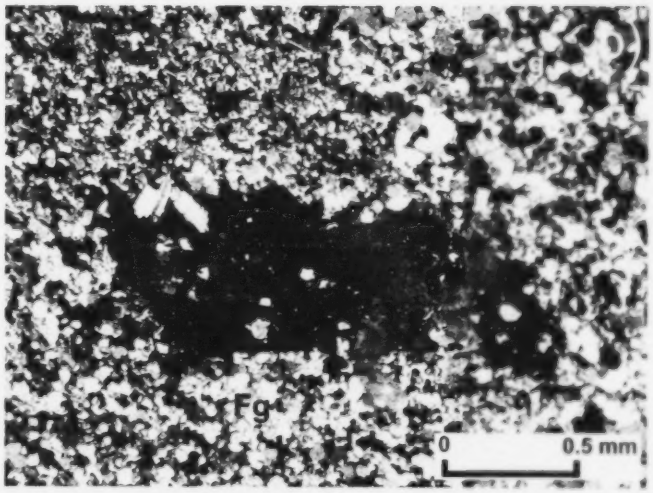


Figure 5b. Rocks of the Mount Brittain Formation at the Maliseet South Zn occurrence. Photomicrograph shows sample from drillhole ML-97-2 at approximately 174 m, under crossed nicols. Fg = fine-grained, Cg = coarse-grained.

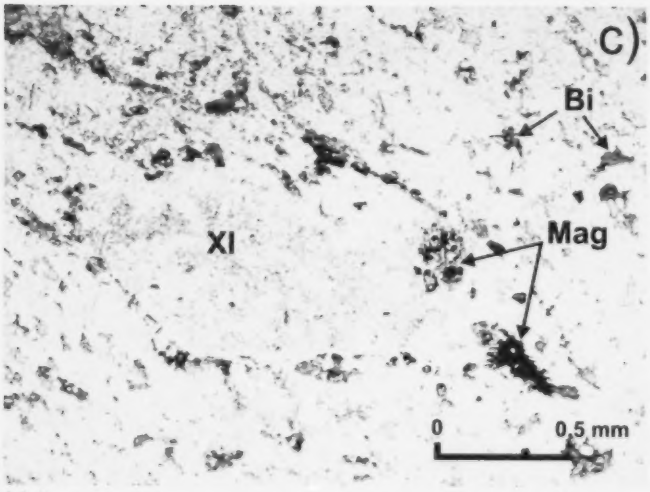


Figure 5c. Same as Figure 5b, but with plane polarized light. Bi = biotite, Mag = magnetite, Xl = possible relict phenocryst.

LITHOGEOCHEMISTRY

Ten samples were collected from drillhole ML-97-2: six from the Goodwin Lake Gabbro, three from the Mount Brittain Formation, and one from the sulphide zone. The samples were analyzed for major elements, trace elements, and rare-earth elements to determine the genetic link, if any, between the sulphide zone and its immediate host rocks.

Major Elements

On the basis of the $Na_2O + K_2O$ vs SiO_2 plots, the sample suite has been divided into two populations: gabbro and felsic volcanic rocks (Fig. 6a). The fairly unaltered nature of the Goodwin Lake Gabbro makes it feasible to use alkali-element ratios as a determinate of rock type. Samples of the Goodwin Lake Gabbro plot definitively in the tholeiitic field on the AFM diagram, whereas samples of the Mount Brittain Formation plot within the calc-alkaline field (Fig. 6b).

Trace Elements

The Middle Ordovician rocks of the BMC have been subjected to polyphase deformation. In places they have undergone lower-greenschist-grade metamorphism as well as seawater-induced hydrothermal alteration. Because both events can result in significant alkali mobility (Lentz and Goodfellow 1994; Lentz 1996), it is preferable to use high-field-strength elements for protolith determination of BMC rocks.

On the Zr/TiO_2 vs Nb/Y discrimination diagram, samples of Goodwin Lake Gabbro plot mostly in the subalkaline basalt field, except for one sample that falls in the alkaline basalt field (Fig. 6c). The Mount Brittain samples straddle the rhyolite and rhyodacite/dacite fields. Their transitional position is typical of samples from both the Mount Brittain and the Nepisiguit Falls formations, the latter of which appears elsewhere in the BMC (Rogers and van Staal 1996; Rogers et al. 2003).

Rogers and van Staal (1996) distinguished between different populations of BMC felsic volcanic rocks on the basis of Zr–Y ratios. Specifically, rocks of the Spruce Lake Formation give $Zr/Y \leq 4.3$, whereas rocks of the Tetagouche Group give $Zr/Y \geq 4.3$. The three felsic samples of Mount Brittain Formation obtained from the bottom of drillhole ML-97-2 — those being samples ML-97-152.5, -174, and -182 (Table 1) — have Zr–Y ratios of 3.4 to 6.3. Such values straddle the boundary between the Spruce Lake Formation and the Tetagouche Group on the Y vs Zr plot. A refinement of this diagram using Y/Ti vs Zr/Ti (Rogers et al. 2003) shows that the felsic samples also straddle the line separating the California Lake and Tetagouche groups (Fig. 6d).

All three Mount Brittain samples show some mineralization and may have undergone a degree of mass change. Nonetheless, the two least-altered samples (ML-97-174 and -182) have fairly high

Table 1. Lithogeochemical data from the Maliseet South Zn occurrence.

Sample			Goodwin Lake				Mineralized	Mount Brittain		
Unit			Gabbro				Zone	Formation		
and No.	ML-97-2 -030.4	ML-97-2 -071.5	ML-97-2 -095.3	ML-97-2 -100.4	ML-97-2 -113.1	ML-97-2 -116.4	ML-97-2 -139.8	ML-97-2 -152.5	ML-97-2 -174	ML-97-2 -182
Element										
wt %										
SiO_2	50.89	50.2	43.63	46	50.57	51.28	35.44	70.23	77.28	78.4
Al_2O_3	17.59	14.63	27	13.69	16.04	16.18	13.19	13.64	11.11	11.5
Fe_2O_3	8.79	14.37	14.4	17.24	10.88	10.71	22.08	4.8	2.63	1.51
MgO	7.84	7.58	6.41	7.75	6.21	5.8	5.86	2.96	1.85	1.08
CaO	9.36	6.79	1.98	8.87	10.11	9.61	3.51	2.99	1.35	0.66
Na_2O	2.18	1.74	1.12	1.75	2.6	2.66	2.09	2.16	2.35	3.29
K_2O	0.58	0.83	0.78	0.43	0.47	0.69	0.99	1.3	1.84	2.66
TiO_2	0.98	2.06	2.03	1.86	1.73	1.57	0.87	0.55	0.18	0.17
P_2O_5	0.09	0.08	0.01	0.26	0.18	0.22	0.13	0.11	0.02	0.005
MnO	0.15	0.18	0.1	0.2	0.17	0.16	0.18	0.08	0.05	0.03
Cr_2O_3	0.036	0.027	0.028	0.044	0.022	0.027	0.01	0	0.01	0.002
LOI	1.3	1.3	2.3	1.6	0.8	0.9	6.8	0.9	0.9	0.5
TOT/C	0.06	0.1	0.07	0.07	0.07	0.07	0.02	0.06	0.04	0.04
TOT/S	0.04	1.85	2.83	2.83	0.19	0.22	13.1	0.24	0.21	0.06
SUM	99.81	99.82	99.81	99.74	99.81	99.82	91.19	99.78	99.65	99.85
ppm										
Ag	0.05	0.05	0.1	0.2	0.05	0.05	12.8	0.3	0.3	0.05
As	5.6	2.5	4.6	1.9	1.8	2.5	18.9	31.4	6.5	6
Au (ppb)	0.25	2.4	6.3	3	1.1	0.9	56.7	4.7	1.8	3
Ba	145	160	100	102	126	152	272	486	688	388
Bi	0.1	0.2	0.2	0.3	0.05	0.1	1.6	0.2	0.3	0.1
Cd	0.2	0.1	0.1	0.1	0.05	0.1	202.7	0.8	2.9	0.1
Co	32.2	83.4	64.8	119.5	35.7	34.1	4.6	4.5	0.5	0.25
Cs	1.3	1.5	2.4	0.4	0.5	0.6	1.5	3.9	3.4	1.7
Cu	15.9	93	132.2	653.1	17.8	26.3	380.8	53.8	11.1	3.2
Ga	15.8	16	33.1	17.9	19	17.8	18.2	18.7	17	14
Hf	1.2	2.1	2.5	1.2	2.3	2.4	3.5	8.9	6.8	8
Hg	0.03	0.005	0.01	0.01	0.005	0.005	30.6	0.16	0.52	0.02
Mo	0.8	1	2.6	0.8	1.4	0.8	3.6	2	5	0.5
Nb	4	8.5	16.9	7	6.6	7	16.6	16.2	17.2	19.7

Note: Sample locations are marked on the inset of Figure 3. Analyses are by ACME Analytical Laboratories Ltd., Vancouver, British Columbia.

Zr–Ti ratios and occur close to the field of felsic volcanic rocks from the California Lake Group. This chemistry, coupled with tectonostratigraphic relationships elsewhere along strike (van Staal et al. 2002), supports assignment of these rocks to the Mount Brittain Formation rather than to the Nepisiguit Falls Formation.

Table 1 *(cont'd)*. Lithogeochemical data from Maliseet South Zn occurrence.

Sample	Goodwin Lake Gabbro						Mineralized Zone	Mount Brittain Formation		
Unit and No.	ML-97-2 -030.4	ML-97-2 -071.5	ML-97-2 -095.3	ML-97-2 -100.4	ML-97-2 -113.1	ML-97-2 -116.4	ML-97-2 -139.8	ML-97-2 -152.5	ML-97-2 -174	ML-97-2 -182
Element										
ppm										
Ni	38.5	108.3	110.3	234.6	9.6	15.7	31.2	15.5	3	1.9
Pb	11.4	4.7	4.7	7	2.2	3.8	7804.5	48.9	165.1	6.7
Rb	24.1	33.5	48.7	13.6	15.8	21.9	24.3	63.9	60	52.7
Sb	0.2	0.1	0.2	0.05	0.05	0.1	8.2	0.4	0.7	0.4
Sc	21	32	12	36	35	32	20	17	15	16
Sn	2	0.5	0.5	0.5	1	1	10	3	4	4
Sr	220.8	196.7	84.8	270.7	318.5	305.7	128.3	221.8	290.5	205.4
Ta	0.4	0.7	1.4	0.4	0.6	0.4	1.4	1.2	1.5	1.6
Th	1.8	3.6	3	1.3	1.9	2.8	2.9	14	18.6	18.1
Tl	0.1	0.1	0.2	0.1	0.1	0.1	2.1	0.4	0.2	0.1
U	0.6	0.9	1	0.9	0.8	0.6	1.2	2.7	3.2	4.1
V	110	247	329	292	273	234	117	36	6	2.5
W	2.1	5.2	3.2	2.7	2.4	3	3.4	4.3	10.9	4.1
Y	17.5	16.1	10.6	24.2	30.3	32	26.5	49.5	60.5	44.6
Zn	78	44	27	61	31	40	95482	405	1487	94
Zr	42.2	72.2	98.3	48.6	72.7	77.8	159.1	309.9	207.8	210.3
La	9.3	11.6	13.9	12.8	15	18.1	28.9	49.4	50.6	52.8
Ce	17.9	21.7	27.1	26.2	33.1	38.6	57.2	101.9	103.3	105
Pr	2.31	2.59	3.08	3.49	4.36	5.11	6.77	11.55	12.4	12
Nd	9.7	10.4	12.1	15.1	18.9	18.9	28.1	45.4	48.5	47.4
Sm	2.5	2.3	2.2	3.9	4.4	5	6.2	8.9	10.4	9.5
Eu	1.15	0.9	0.78	1.35	1.58	1.71	1.68	2.06	1.41	1.25
Gd	2.9	2.38	2.16	4.53	5.16	5.43	5.18	9.17	9.9	8.89
Tb	0.5	0.39	0.31	0.65	0.91	0.91	0.72	1.35	1.85	1.44
Dy	3.02	2.58	1.72	3.87	5.27	5.52	3.71	7.98	9.87	7.93
Ho	0.62	0.55	0.38	0.86	1.15	1.11	0.82	1.63	2.01	1.46
Er	1.84	1.83	1.06	2.54	3.41	3.32	2.56	4.92	5.84	4.55
Tm	0.23	0.23	0.1	0.37	0.42	0.45	0.31	0.74	0.79	0.66
Yb	1.7	1.7	1.05	2.02	2.77	2.98	2.11	4.73	4.83	4.13
Lu	0.29	0.38	0.19	0.39	0.43	0.41	0.38	0.77	0.8	0.67

Rare-Earth Elements

Felsic volcanic rocks of the Mount Brittain Formation have moderately steep rare-earth-element profiles that show an average La_n–Lu_n ratio of 7.14, and moderately strong negative Eu anomalies that show an Eu–Eu* ratio of 0.325 for the two least-altered samples. This combination of high profiles for light rare-earth elements, and negative Eu anomalies, is characteristic of felsic volcanic rocks in the Bathurst Mining Camp (Fig. 7).

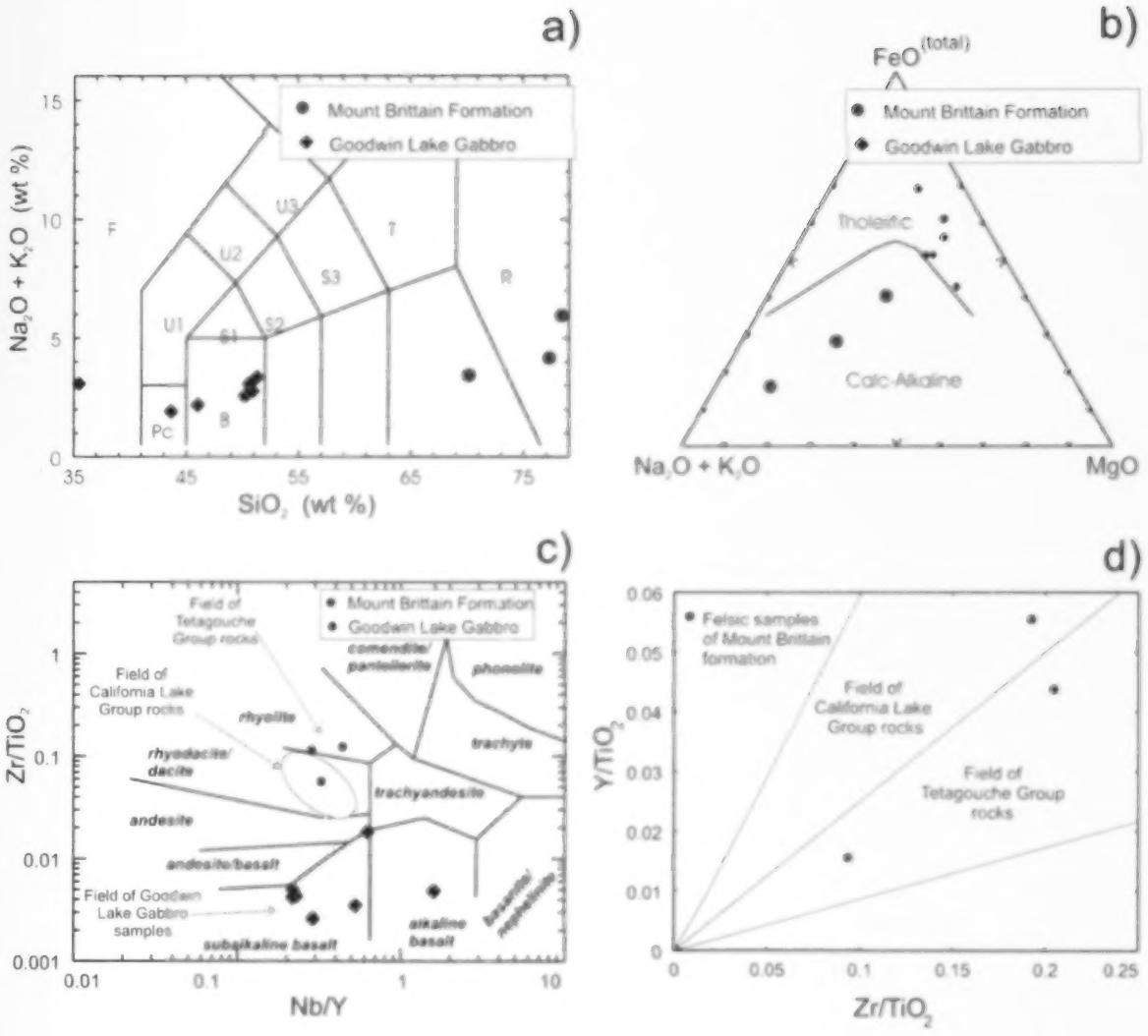


Figure 6. Lithogeochemical discrimination diagrams for samples in Table 1. a) $Na_2O + K_2O$ vs SiO_2 diagram from Le Maitre et al. (1989). b) A–F–M diagram from Irvine and Baragar (1971). c) Zr/TiO_2 vs Nb/Y diagram from Winchester and Floyd (1977). Field boundaries for Tetagouche and California Lake groups from Rogers et al. (2003). d) Y/TiO_2 vs Zr/TiO_2 diagram from Rogers et al. (2003).

All samples of the Goodwin Lake Gabbro have moderately flat rare-earth-element profiles. Their La_n–Lu_n ratios for the four least-altered rocks range from 3.1 to 3.6, averaging 3.38. The six gabbro samples exhibit weakly negative to flat Eu anomalies and Eu–Eu* ratios of between 0.79 and 1.0 (Table 1). The flat Eu profiles are expected, given the abundant feldspar in the intrusions and the ready fractionation of Eu into feldspar. Figure 7 shows chondrite-normalized rare-earth-element profiles for all samples in Table 1.

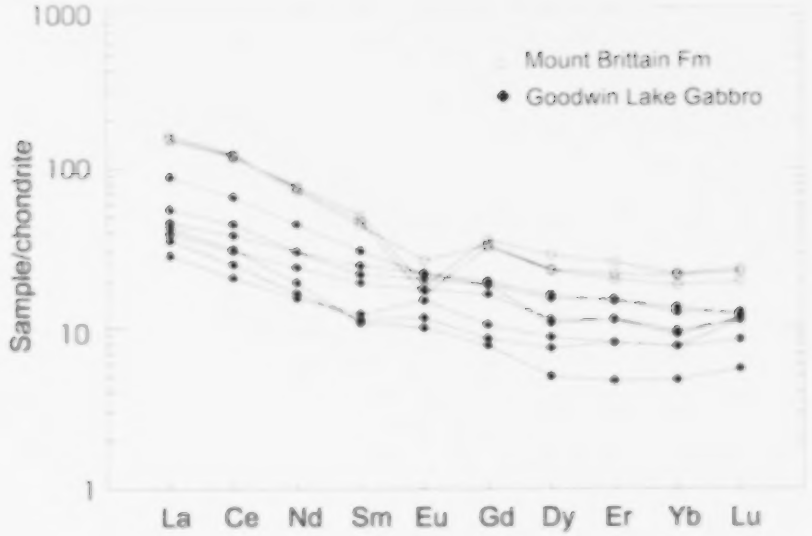


Figure 7. Chrondite-normalized plot for samples in Table 1. Normalization factors are from Nakamura (1974).

MINERALIZATION

Cu–Ni-sulphide mineralization in the Goodwin Lake Gabbro has been examined by several exploration companies since the 1960s including Noranda Exploration Co. Ltd., Conwest Exploration Co. Ltd., MicMac Mines Ltd., Minbanco Corp., and Granges Exploration Ltd. The most successful of these efforts was conducted by Granges, which intersected 1.28 wt % Cu and 1.16 wt % Ni over 9.15 m in drillhole R-55, and 1.64 wt % Cu and 0.56 wt % Ni over 5.15 m in drillhole R-50 (O'Donnell 1989). The two largest occurrences of Cu–Ni sulphides in the Goodwin Lake Gabbro were located at Maliseet North and Maliseet East (Fig. 2; Paktunc 1988).

Magmatic Cu–Ni mineralization also is present at Maliseet South Zn, although not in core from drillhole ML-97-2. The most prevalent form of such mineralization is as disseminated to patchy pyrrhotite ± chalcopyrite and pentlandite that formed as interstitial fill to cumulate silicate phases in the ultramafic body (Paktunc 1988). These same sulphide phases occur less commonly as pods and irregular lenses that, in places, contain more than 80% sulphide material over widths of 1 to 2 m; the remaining 20% consists of rounded aggregates or irregular masses of silicate phases (mostly plagioclase) variably altered to sericite. Rounded pyroxene crystals that exhibit overgrowths of amphibole and/or biotite occur locally within the sulphides.

The most noteworthy type of mineralization at Maliseet South Zn appears only in core collected from drillhole ML-97-2. There, it presents as a sulphide zone intersected between 121 and 141 m, appearing as semi-massive to massive lenses of variable width within the host gabbro intrusion (Fig. 3, 8a). The mineralization consists primarily of pyrrhotite, sphalerite, and galena, but includes less

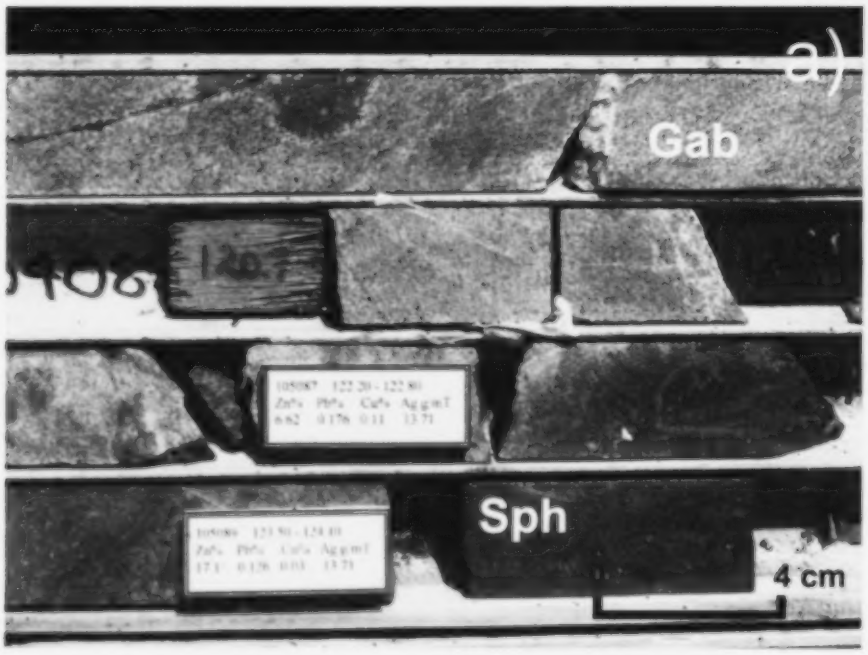


Figure 8a. Drill core from the Maliseet South Zn occurrence, drillhole ML-97-2. Core shows upper contact of the mineralized Zn zone at approximately 122 m. Note the vein and 'pod' of sulphide at beginning of the top run. Gab = gabbro, Sph = sphalerite.

abundant pyrite and chalcopyrite (Fig. 8b–d). The zone averages 5.93 wt % Zn, 0.24 wt % Pb and 0.09 wt % Cu over the 15.9 m width between 122.2 and 138.1 m (Mersereau 1998a, b). Within the zone, a more massive, Zn-rich lens was delineated toward the footwall side between 132.5 and 138 m. Grades obtained from this lens were fairly high, with the best assay, 17 wt % Zn over 0.6 m, being reported from the interval between 133.2 and 133.8 m (Mersereau 1998d).

The exact nature of the contact relationship between the Zn-rich lens and the host gabbro is unclear. The contact appears to be sharp or slightly gradational over a width of 10 cm. Mineralization at the top of the zone (at 121–123 m) decreases gradually into the hanging wall over a width of 1 to 2 m, whereas mineralization below the Zn-rich massive lens decreases toward the footwall over a width of about 3 m. The massive lens is separated from felsic volcanic rocks of the Mount Brittain Formation by at least 6 m of unmineralized to weakly mineralized gabbro.

This type of Zn-sulphide mineralization associated with minor Pb sulphide is problematic from a deposit modelling perspective, because it has not been previously recognized in mafic-intrusion-hosted deposits. The question arises: Does the occurrence represent a new type of deposit, or is it instead a stoped block of VMS mineralization from the California Lake Group?

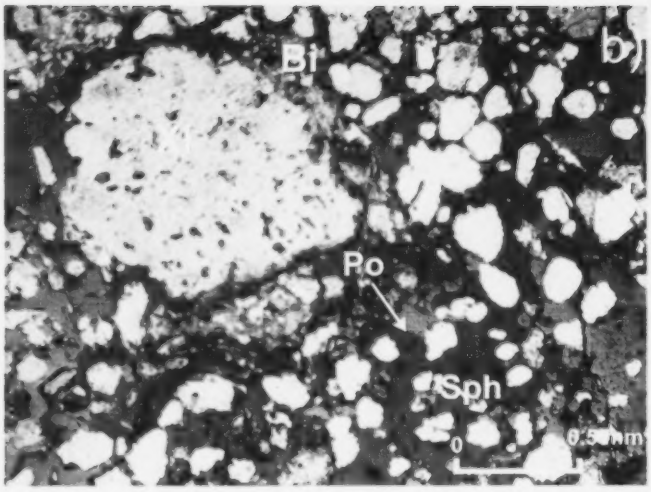


Figure 8b. Mineralization at the Maliseet South Zn occurrence. Photomicrograph shows semi-massive to massive sulphides, in reflected light, from drillhole ML-97-2, sample ML-97-125.7. Bi = biotite, Po = pyrrhotite, Sph = sphalerite, Xl = large feldspar crystal showing igneous 'wormy' texture.

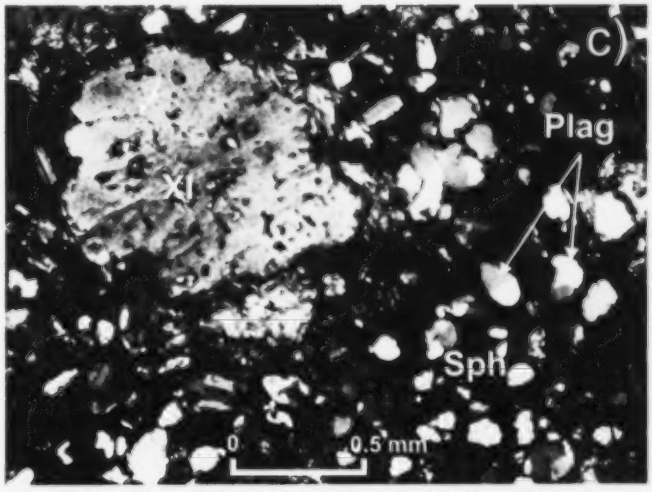


Figure 8c. Same as in Figure 8b, but under crossed nicols. Plag = plagioclase, Sph = sphalerite, Xl = large feldspar crystal showing igneous 'wormy' texture.

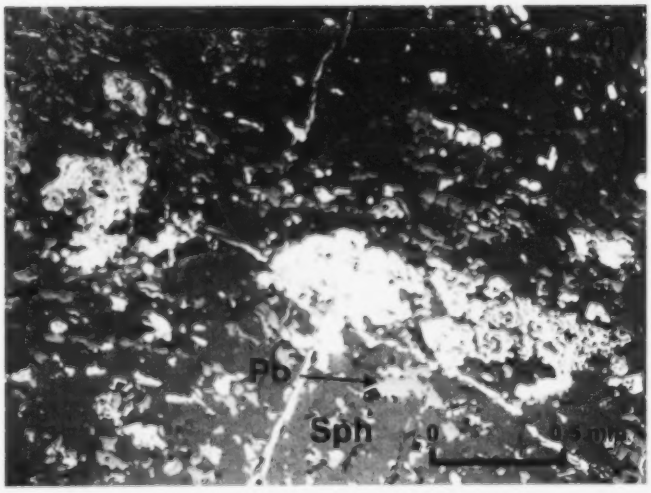


Figure 8d. Mineralization at the Maliseet South Zn occurrence. Photomicrograph shows massive sulphides in reflected light from drillhole ML-97-2, sample ML-97-139.8. Po = pyrrhotite, Sph = sphalerite.

Throughout drillhole ML-97-2, sulphide and/or oxide mineralization consistently shows a close spatial relationship to biotite-rich zones in the gabbro (Fig. 4, 8). It is assumed that biotite was formed at these sites due to higher H_2O activity, although why aH_2O should be higher near sulphides is unknown. In addition, it is possible that the biotite resulted from contact metamorphism coincident with intrusion of the Mount Elizabeth Granite, as Mount Brittain rocks also contain biotite that locally appears to postdate feldspar in the groundmass (Fig. 5b, c). In this scenario, chlorite and pyrite in the Mount Brittain rocks could have been scavenged for the Mg and Fe needed to form biotite.

Highly mineralized sample ML-97-2-139.8 and weakly mineralized sample ML-97-2-152.5 (Table 1) display Eu anomalies midway between those of the unmineralized Mount Brittain and Goodwin Lake Gabbro samples, and have an average Eu–Eu* ratio of 0.625. Eu anomalies in VMS-style sulphide mineralization generally mirror those of rocks in the footwall. Under hydrothermal conditions of high temperature (>350°C) and low pH, however, Eu^{+3} is reduced to Eu^{+2}, making it far more soluble than other heavy rare-earth elements in the fluids (Gale et al. 1997). Eu-enriched fluid is capable of precipitating Eu in exhalative VMS bodies. As the fluid mixes with seawater, precipitation takes place, because Eu becomes insoluble as the pH rises and the temperature drops — hence the characteristically positive Eu anomalies in VMS deposits (Gale et al. 1997).

The Eu anomalies in mineralized samples from Maliseet South Zn likely resulted from the mixing of VMS mineralization formed at low temperature (Eu/Eu* ≈0.3) with gabbro (Eu/Eu* ≈0.9). Additional evidence supporting this hypothesis comes from petrographic analyses of sample ML-97-125.7 (Fig. 8b, c). Here, abundant rounded grains of mostly feldspar are seen within a sulphide matrix. The feldspar crystals evidently are unaffected by deformation, as they show no sign of undulatory extinction. Yet their rounded appearance implies either mechanical reworking or, more likely, chemical disequilibrium with the enclosing sulphides.

The presence of large, corroded crystals of feldspar displaying igneous growth textures implies that at least some of the silicates in this sample were derived from the gabbro (Fig. 8b, c). The feldspar crystals could be explained as the result of mixing crystal mush from the Goodwin Lake Gabbro with introduced sulphides of VMS mineralization. In this case, the resulting Eu–Eu* ratios should plot somewhere between those of gabbro and the massive sulphides. Although only a small number of petrographic samples were collected, it is interesting to note that the proportion of silicate to sulphides gradually decreases toward the contact with Mount Brittain rocks.

An alternative hypothesis of formation proposes the near-total assimilation of a stoped block containing both massive sulphides and adjacent Mount Brittain rocks. Such an event could result in the same texture and would yield Eu–Eu* ratios significantly higher than those of the gabbro.

Table 2. $\delta^{34}S$ data from Maliseet South Zn occurrence, drillhole ML-97-2.

Depth (m)	Rock Type	$\delta^{34}S$
30.4	gabbro	9.33
100.4	gabbro	9.32
122.5	mineralized sulphide zone	8.78
124.0	mineralized sulphide zone	8.16
126.5	mineralized sulphide zone	8.41
129.5	mineralized sulphide zone	8.31
137.1	Zn-rich lens	9.03
	Average $\delta^{34}S$	8.76

Note: Analyses were conducted by Alison Pye, Memorial University of Newfoundland.

S-isotope Studies

As part of the present investigation, seven samples from Maliseet South Zn were analyzed to determine if differences exist in the sulphur isotope signatures of the Zn mineralization and Cu–Ni mineralization found in the Goodwin Lake intrusion (Table 2). The samples were collected from drillhole ML-97-2, beginning in the gabbro and passing through the massive-sulphide lens. Gabbro at the top of the drillhole returned a $\delta^{34}S$ value of +9.3 ‰, whereas gabbro samples closer to the Zn-rich sulphide lens gave values ranging from +8.3 ‰ to +8.8 ‰. The lower side of the sulphide lens (at 137.1 m) gave a $\delta^{34}S$ value of +9.03 ‰. Generally, the $\delta^{34}S$ values of the unmineralized gabbro and the sulphide lens were remarkable consistent, ranging from +8.2 ‰ to +9.3 ‰.

A sulphur-isotope study by Paktunc (1988) of the Maliseet East and Maliseet South occurrences showed that $\delta^{34}S$ values for Cu–Ni-sulphide mineralization in the Goodwin Lake Gabbro vary from +2.7 ‰ to +18.9 ‰.The wide range in $\delta^{34}S$ values implies significant variation in the degree of mixing between mantle-derived sulphur and introduced crustal sulphur (Ohmoto and Rye 1979). The narrow range in $\delta^{34}S$ values returned during the present study indicates that sulphur in both the host rock and mineralized zone was derived from essentially the same crustal source. A possible source of sulphur can be seen in the hanging wall of the Maliseet South Zn occurrence, which consists of volcanic rocks belonging to the Mount Brittain Formation of the California Lake Group. Elsewhere in the Bathurst Mining Camp, these volcanic rocks are known to contain VMS deposits. Moreover, the average $\delta^{34}S$ value of +5.92 ‰ for the VMS deposits (Goodfellow et al. 2003) approaches that found in the massive-sulphide lens at Maliseet South Zn.

Given the high Zn and anomalously high Pb values reported, it seems likely that the Zn-rich sulphide lens at Maliseet South Zn represents a block of VMS incorporated into the Goodwin Lake intrusion. Sulphur found in the gabbro and the associated Cu–Ni mineral occurrences therefore could have originated in large part from magmatic stoping and assimilation of VMS-bearing country rock belonging to the Mount Brittain Formation.

Discussion

Both types of mineralization at Maliseet Mountain — the Cu–Ni sulphides associated with the mafic intrusion, and the Zn–Pb massive sulphides — show remarkably similar $\delta^{34}S$ values. The additional similarity of $\delta^{34}S$ values found in the Zn–Pb mineralization and the VMS mineralization hosted by the California Lake Group (Goodfellow et al. 2003) supports the proposal of van Staal et al. (2002), which hypothesizes placement of a host felsic volcanic sequence in the Mount Brittain Formation. This scenario suggests that sulphur in the gabbro resulted from contamination by rocks belonging to the Mount Brittain Formation. Many examples exist elsewhere in which sulphides hosted by mafic intrusions are interpreted as having acquired their sulphur through the consumption of sulphur-rich wall rocks (Paktunc 1988; Eckstrand 1996).

The presence of massive sulphides in rocks hosting the Goodwin Lake intrusion is important for two reasons. First, sulphur-rich host rocks enhance the likelihood of discovering economically viable magmatic Cu–Ni-sulphide deposits. Second, the recognition of VMS-style mineralization, regardless of whether it is in allochthonous country rock or stoped xenolithic blocks, improves the likelihood of discovering VMS mineralization in this southwestern part of the BMC.

The appearance of late biotite in Mount Brittain rocks and the Goodwin Lake Gabbro indicates that, in both instances, biotite may be the product of contact metamorphism related to intrusion of the Mount Elizabeth Granite. On the other hand, the close spatial relationship between sulphide mineralization and biotite in the gabbro possibly indicates that biotite formed concurrently with sulphide precipitation and resulted from contamination by host rocks during gabbro emplacement. The latter hypothesis also could explain the presence of biotite in Mount Brittain rocks immediately adjacent to the gabbro.

Cu–Ni-sulphide mineralization in tholeiitic intrusions generally is concentrated near the intrusion base. It consists of pyrrhotite-pentlandite-chalcopyrite-pyrite, and magnetite (Eckstrand 1996). The two most notable occurrences of Cu–Ni mineralization in the Goodwin Lake Gabbro are concentrated close to the eastern, and presumed lower, contact. Yet at Maliseet South Zn, the Cu–Ni mineralization and Zn-rich lens occur near the western, or presumed upper, contact. This contrast provides evidence that mineralization at Maliseet South Zn is controlled more by proximity to a sulphur source, that being the Mount Brittain Formation, than to any gravitational concentration derived from an initially sulphur-enriched magma.

CONCLUSIONS

The Siluro–Devonian Goodwin Lake Gabbro is one of only four intrusions in New Brunswick to host magmatic Cu–Ni sulphides. Cu–Ni-sulphide mineralization in the gabbro was enhanced by the introduction of crustal sulphur through contamination of the intrusion by Middle Ordovician VMS mineralization. These massive sulphides probably were derived from the Mount Brittain Formation of the California Lake Group. The mechanism of contamination from an external sulphur source has been invoked elsewhere to explain magmatic sulphide deposits in many mafic intrusions (Eckstrand 1996).

High-grade (10 wt %) Zn associated with elevated Pb values in the massive-sulphide zone is readily explained by the assimilation of Middle Ordovician VMS mineralization. The hypothesis is supported by the presence of elevated levels of elements such as Ag, Au, Cd, Cu, Mo, and Sn in the sulphide zone (e.g. ML-97-2-139.8 in Table 1). These elements tend to be similarly elevated in VMS-style mineralization from the BMC (Lentz 1995).

These data represent the first suggestion of VMS-type mineralization along the southwestern margin of the BMC. The mineralization appears to be a stoped block, as it is found within the gabbro, albeit within 10 m of the intrusion margin. For the most part, the block has been digested by the intrusion and its sulphides remobilized. The latter observation may not bode well for the discovery of additional VMS 'blocks' in the intrusion. Nonetheless, the recognition of Zn-rich sulphides 1 km to the south at roughly the same horizon suggests the possibility of a significant VMS deposit in this area.

The stratigraphic position of what appears to be VMS mineralization in the Mount Brittain Formation at Maliseet South Zn resembles that at the Murray Brook and Restigouche deposits. In all three instances, the mineralization is hosted within a volcaniclastic facies of the Mount Brittain Formation immediately below the felsic volcanic facies. The presence of evidently abundant sulphide mineralization in the Goodwin Lake Gabbro enhances the potential of finding additional magmatic Cu–Ni occurrences in this mafic intrusion.

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